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Process planning for fixturing of custom machined implants

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by

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ABSTRACT

This thesis presents a process planning methodology for orienting and fixturing bone prior to the rapid machining of custom bone implants. The motivation is to automatically create custom bone implant fragments that will fill voids caused by extreme trauma. Fixturing can be one of the biggest challenges of any manufacturing process, in particular, for custom components. ñCNC-RPò is a Subtractive Rapid Prototyping (SRP) process which employs the concept of sacrificial supports for fixturing. The support structures are added to the CAD model prior to tool path planning and subsequently created during the machining process along with the other part features. This method of adding support structures has been proved successful for the machining of industrial components out of cylindrical stock material. Due to the unique position of the implant corresponding to the density distribution within natural bone (stock), it is a challenge to create the same support structures. An alternative approach has been identified which will uniquely address this problem by adding supports externally, in the form of metal screws.

A set of existing algorithms identify the harvesting site of the implant; the algorithms also yield the location and the direction of the support structures in the form of co-ordinates and vectors. The methodology presented in this work provides a novel method to physically add the support structures at precise position and direction utilizing a five axis fixture. Using the principles of inverse kinematics, the rotations and translations are determined. The resulting co-ordinates of the support positions are used to insert the supports.

CHAPTER 1: INTRODUCTION

Sometimes traumatic events like vehicular accidents, high-height falls, or explosions can lead to bone injuries creating voids in the bone. In some of these cases, an implant made up of bone or bone substitute is used as a graft and placed in the void using a surgical procedure.

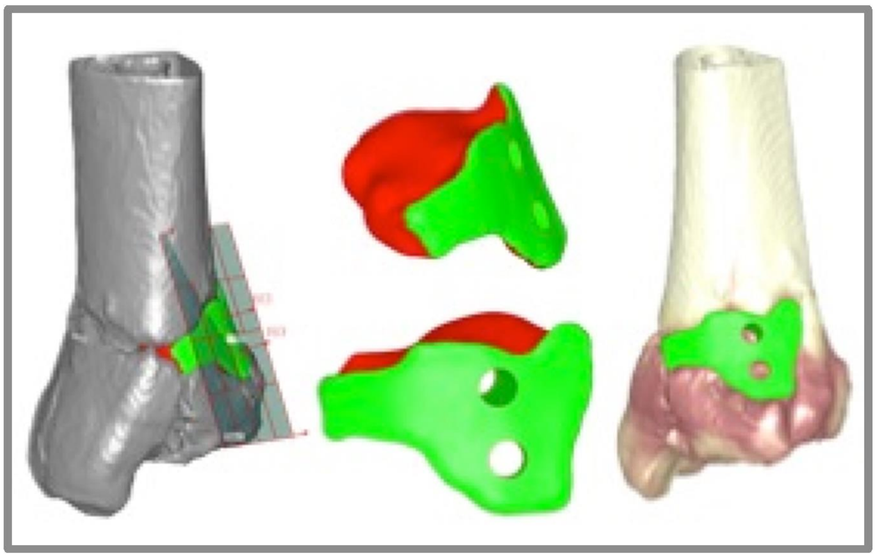

Figure 1 Bone implant and implant grafted at the site

According to the AAOS (American Academy of Orthopedic Surgeons), there are ~6.3 million fractures each year in United States and about 500,000 bone implant procedures per year [1]. In the past, bone implant grafting has relied heavily on the surgeonös ability in cavity preparation and to use hand shaped fillers [2] [3]. This hand crafting process can make it more complex and time consuming [4].

Material injections are used in some cases to fill the voids. Injectable pastes are developed for use as fixation materials. They have two main advantages over pre-shaped materials. They are minimally invasive over surgical procedures and can conform to any shape they are pressed into. Properties like viscosity, setting time and initial mechanical strength play an important role in the success of this process [5].

Several fabrication processes have been utilized to manufacture bone implants. One of them is solvent casting. In this process, the implant is manufactured by adding a polymer solution (poly lactic acid dissolved in an organic solution) into a mold containing a solid porogen (salt crystals). Porogen is removed in post process and is responsible for creating pores [6]. Although solvent casting has been effective, it lacks reproducibility and ability to provide designed pore geometries and morphologies [7].
Rapid Prototyping (RP) technologies are increasingly used for implant manufacturing. RP is a group of a group of technologies used to quickly fabricate a physical part using 3D CAD data. . The basic principle of this technology is that a model is initially generated using a 3D CAD system, it is then divided into layers where each layer is a thin cross section of the part and then parts are made by adding material in layer by layer fashion. Some of the RP technologies employ sacrificial support structures as fixtures to secure the part. These structures are automatically constructed during the build process. These are either made from the same material as of the part or from a secondary material depending upon the intricacy of the machine. These structures support and increase the stiffness of the overhanging features that do not have preceding layer to support them from below. These support structures are subsequently removed in a post processing step.

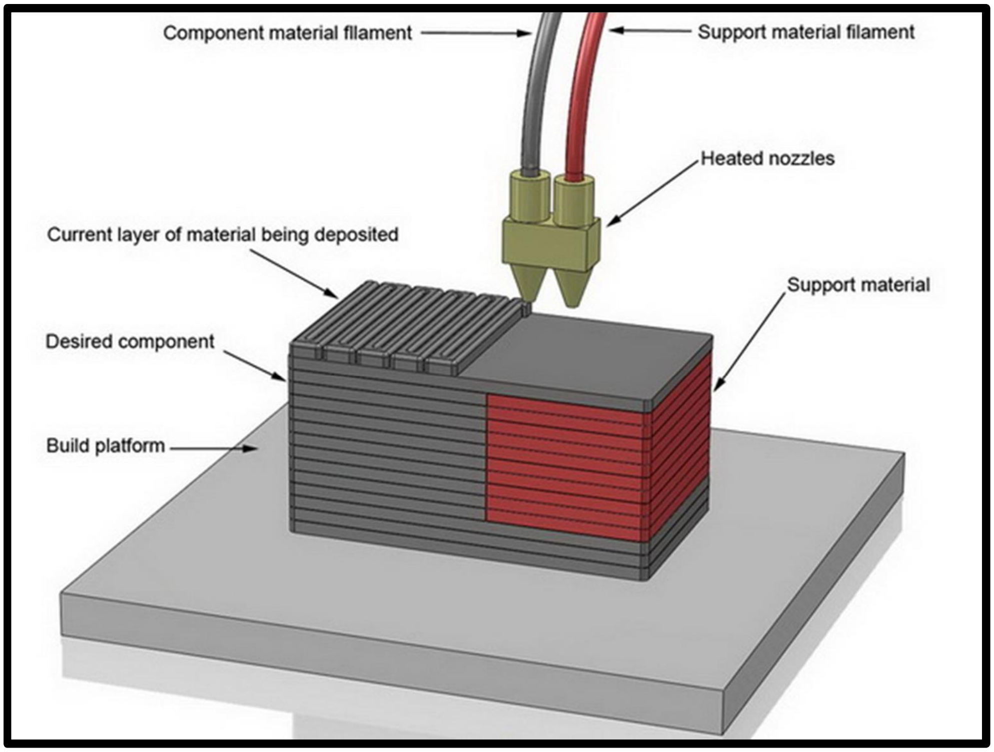

Figure 2 Rapid Manufacturing Technology: Fused Deposition Modeling (FDM)

RP technologies like Stereolithography (SLA), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS), 3 Dimensional Printing (3DP), Laser Engineered Net Shaping (LENS), Fused Deposition Modeling (FDM) have been used successfully in creating custom designed bone implants. These implants have been created using a wide array of clinically relevant materials like Titanium, Co-Cr alloys biopolymers like Ultra high Molecular weight polyethylene (UHMWPE) , Polyurethanes, ceramics like Zirconia, Alumina, Hydroxyapatite, etc. [3] [8] [9] [10] [11] [12]. There are some disadvantages of using these processes for bone implant manufacturing and are listed in the following table.

Table 1 Disadvantages of AM process for Implant Manufacturing [1]

Sr No.	Method	Disadvantages
1.	Stereolithography	Limited choice of material may require furnace post processing (e.g. bio ceramics), high material cost, complex and expensive equipment
2.	Laser Sintering	Materials may thermally degrade during the process, undesired porosity, hard to remove trapped powder, complex and expensive equipment
3.	3D Printing	Hard to remove trapped material, low to medium resolution, powder particles may not bind well, binders are always necessary to bind powders
4.	Fuse Deposition Modeling	Materials may thermally degrade during the process, lower range of material choices, medium resolution

Porosity is compromised in some of the RP processes and it is well established that the bone will infiltrate the pores of an implant provided the implant is initially stabilized and minimal movement occurs between the implant and bone [13]. Implants made from natural bone have unique density distribution throughout its volume. Having a density distribution on the implant similar to the one at the fracture site could allow the parent bone to integrate with the implant effectively as compared with other bio-implants. Hence it can be concluded that the implants made out of allografts could perform better as compared to implants made from the materials mentioned above.

The implants can be harvested from natural bone, assuming some subtractive technique can be applied to machine the geometry. A project that investigates the rapid manufacturing of implants from natural bone stock is being carried out at Rapid Manufacturing and Prototyping Laboratory (RMPL), Iowa State University in collaboration with Orthopedic Biomechanics Laboratory, University of Iowa.

The process starts with CT scan of the patient. Algorithms are developed to carry out the reconstruction of damaged site of patientôs bone [14].

Figure 3 Reconstruction of injured bone

A 3D geometry of the void can be obtained and is used for manufacturing of the derived implant. The 3D CAD model of the implant along with bone density information is utilized to identify the harvesting site in the bone stock. The implant is then harvested using a novel machining method known as CNC-RP.

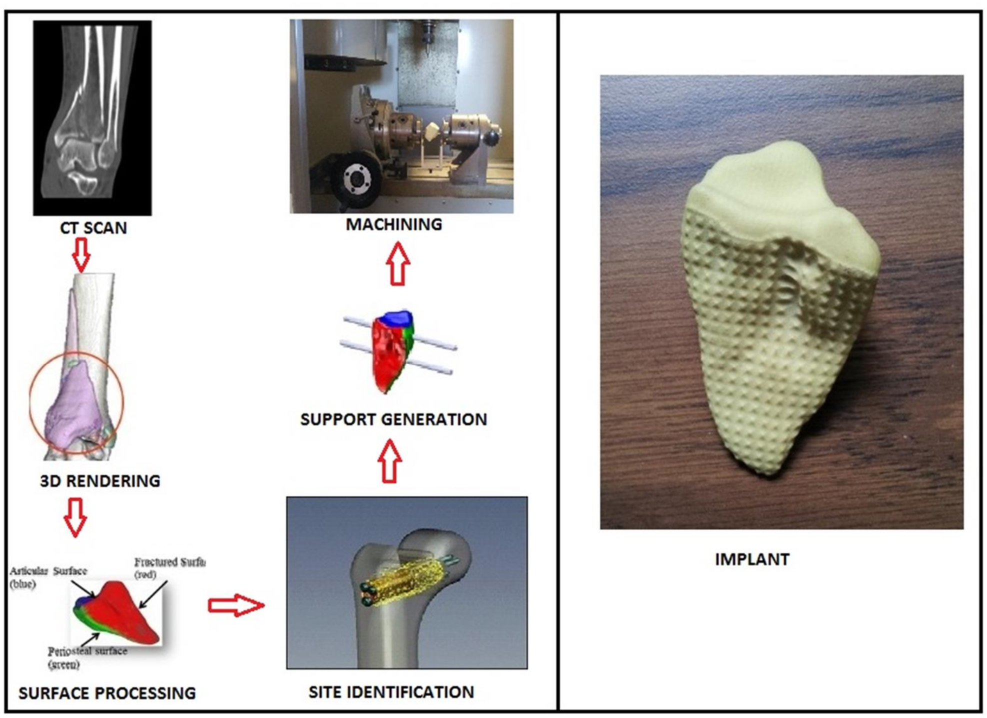

Figure 4 Process overview of implant harvesting from natural bone

CNC Rapid Prototyping (CNC-RP) is an automated rapid machining method that combines CNC machining with the concept of layered manufacturing similar to the AM technologies, however in an opposite approach to create functional 3D parts [15]. CNC-RP is a four axis rapid machining process where the part is machined using a cylindrical stock fixed between two opposing chucks. In order to create the 3D part using CNC-RP, the stock is oriented and machined about one axis of rotation until all necessary surfaces are machined. CNC-RP employs a similar concept of sacrificial supports, instead of adding material to the physical model; the supports are added to the CAD model prior to the tool path planning and subsequently created during the machining process along with other features.

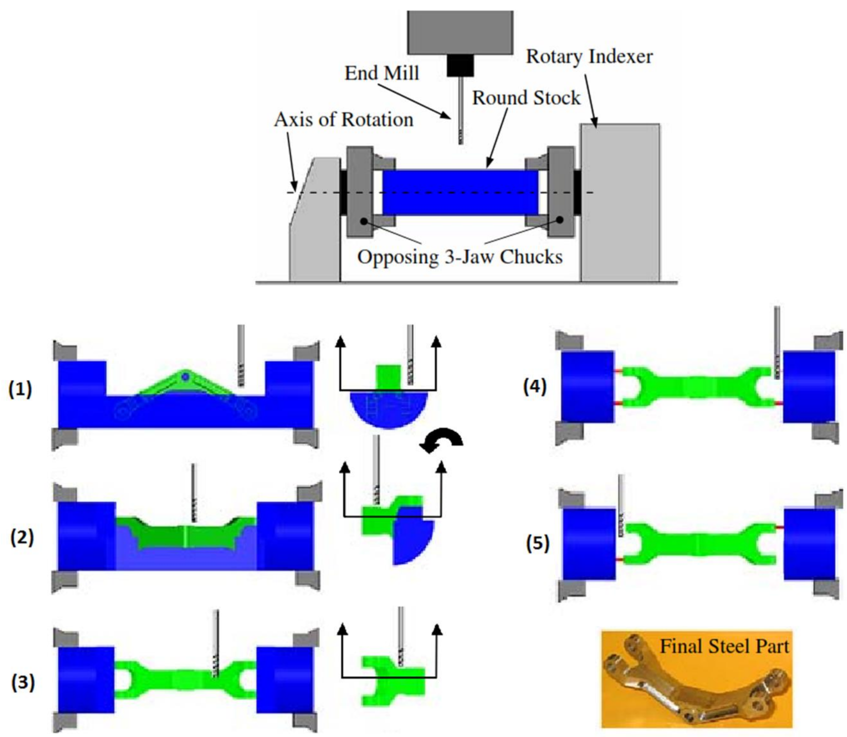

Figure 5 CNC-RP Steps

In order to create 3D parts using CNC-RP, the stock is oriented and machined about one axis of rotation until all necessary surfaces are machined. Rotating the stock about an axis would be a very difficult task if conventional fixturing techniques are used. Hence CNC-RP employs a concept similar to sacrificial support structures in RP technologies.

The requirement for conventional CNC machining is that the block of material must be atleast as big as the part that is to be made. In case of CNC-RP, the supports are implemented as small features to the solid model parallel to the axis of rotation of the part, so the raw material should be in excess along the direction of rotation to create the supports in place during machining. This technique can be classified as automated fixturing for machining and enables saving manual effort for multiple setups.

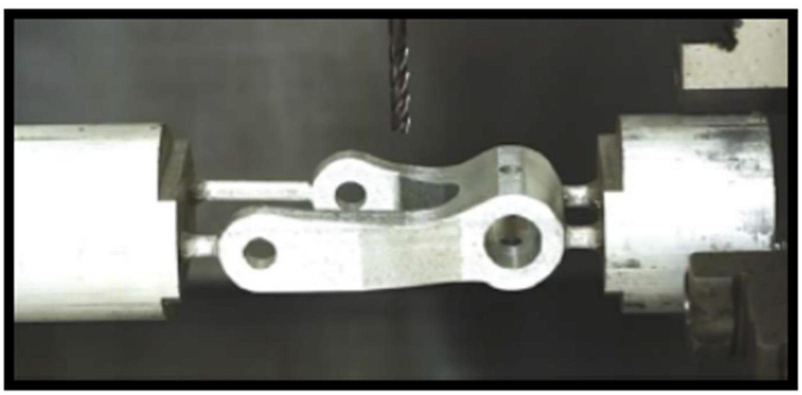

Figure 6 Excess material along axis of rotation for supports

Previous work has shown CNC-RP can be utilized for making functional parts using the automated fixturing in the form of sacrificial supports. Although, to apply the same technique for harvesting bone implants from donor bones is a challenge due to the unique position and orientation of the harvest site corresponding to the required density distribution. If the harvest site is identified at one end of the donor bone then there would not be any excess material to generate the supports during machining.

In order to utilize CNC-RP to form an integrated process for harvesting custom bone implants out of the donor bones, there is a need to develop an alternative fixturing system. One possible solution is to externally insert supports through discs with a grid of holes as shown in Figure 7.

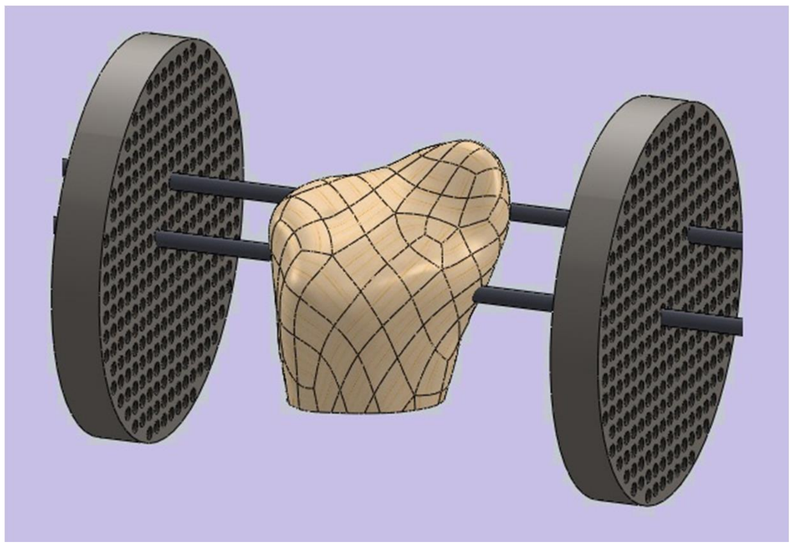

Figure 7 Desired machining fixture that mimics the round stock

This configuration is intended to mimic the round stock required for CNC-RP hence the overarching goal of this thesis is to develop a method to aid in fixturing of the bone between discs using predetermined support locations.

Thesis Layout

The layout of the thesis is as follows. *Chapter 2* provides a literature review which explains different research related to fixturing and a review on some of the non-traditional fixturing techniques. *Chapter 3* is the main chapter of this thesis and describes the algorithms and methodology developed for fixturing of the bone using a five axis positioner. This chapter guides the reader starting from output of the harvesting algorithms to the step prior to machining. *Chapter 4* shows the implementation of these algorithms as an executable project developed in C/C++, taking in input data generated using harvesting algorithms and then finding a solution describing the transformations to be made on the five axis fixtures and also giving grid locations on the discs for sacrificial supports. *Chapter 5* provides conclusion and future work.

CHAPTER 2: LITERATURE REVIEW

Machining is one of the most common manufacturing processes in use today. The raw material is cut into a desired final shape and size by a controlled material removal process, and for any manufacturing operation to be successful the work piece must be located and held in position and orientation. One of the biggest challenges for efficient machining is immobilization, location and support of the parts commonly referred to as *fixturing or work holding*. Also manufacturing has become much more diverse in recent decades, owing to the demand for complex shaped parts with requirements of strict tolerances, broad spectrum of material used for making these parts and a variety of new manufacturing processes developed [16] [17]. All these factors have pressed the need for developing fixture systems, sometimes application specific to satiate the assorted need of the industry and hence a greater amount research is being carried out in this field [18] [19] [20].

Choi et al in their report identify location, support and hold as the three critical purposes of fixturing [21]. The cost of designing and fabricating fixtures can amount to 10-20%of the total manufacturing system costs [18], which is a significant portion.

Traditional fixturing techniques of using vises, clamps, v-blocks etc. requires lot of technical skill and these lack the flexibility to handle parts of arbitrary shapes. One of the flexible fixture solutions is the Reference Free Part Encapsulation (RFPE) developed by Choi et al. which exploits the property of phase change of materials [21]. Phase changes may be temperature induced, electrically induced or a combination of the two. This technique introduces thermal shrink and expansion problems [21]. Some adhesive techniques like Light Activated Adhesive Gripper (LAAG) [22] and Photo Adhesive Workholding (PAW) [23] have also been developed.

A predetermined grid of holes and components can be used to build a fixture [19]. The use of modular fixtures component not only eliminates the need of single-purpose fixtures but also comparatively takes greater variability into account [24].

Shirinzaadeh [25] in his work classifies various fixturing techniques as shown in Figure 8.

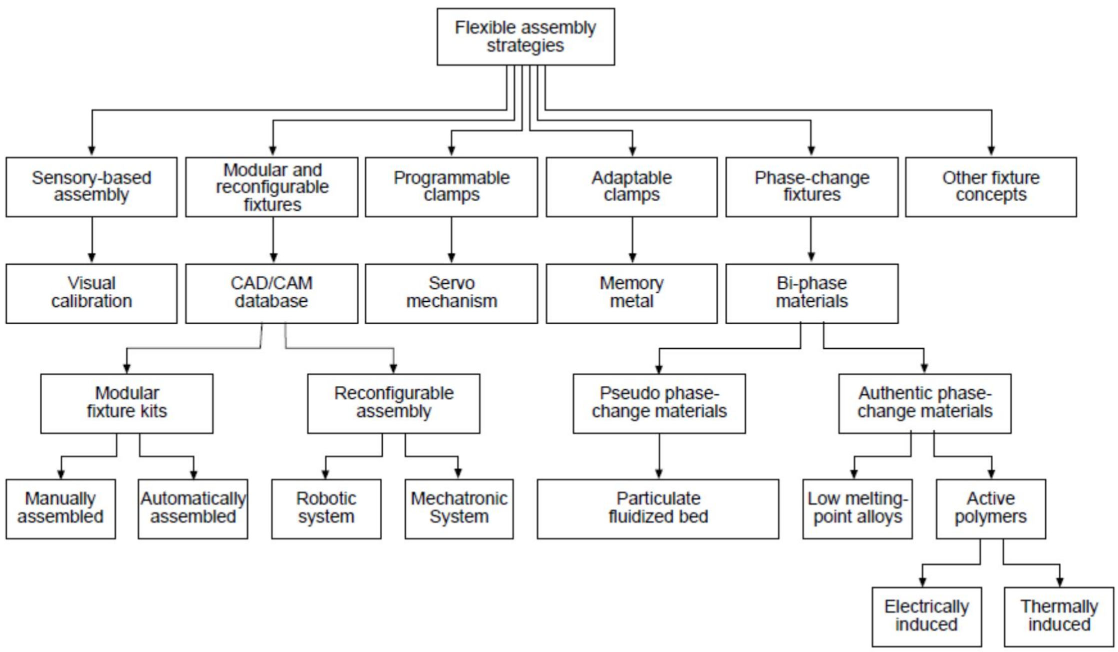

Figure 8 Classification of fixture systems [25]

Artificial intelligence techniques can be used in conjunction with 3D solid CAD and database systems and greater emphasis can be put on the integration of the intelligent fixture design systems with robotic fixture assembly, knowledge based process planning and intelligent production scheduling system [26] [27]. The computer based automation of the design activities is commonly referred to as computer aided fixture design (CAFD) [20]. Design of fixtures is a complicated process that highly depends on the experience level of the engineer [28]. CAFD systems provide the fixturing knowledge combined with the CAD software capabilities to reduce the experience engineer dependence [29].

In RP processes, sacrificial support structures which are automatically added during the build process serve the function of a fixture. These structures support and increase the stiffness of the overhanging features that do not have preceding layer to support them from below. These sacrificial supports are then removed in a post processing step. Previous research has addressed issues in the design of these structures particularly for the development of the stereo-lithography and fused deposition modeling. CNC-RP employs a similar concept of sacrificial supports; however in the opposite approach. Instead of adding the material to the physical model, the supports are added to the CAD model prior to tool path planning and subsequently created during the machining process along with the other part features [30].

CHAPTER 3: METHODOLOGY

The primary objective of this work is to fixture a bone between discs using predetermined support locations. In order to position and orient the bone stock, a five axis positioner is used. The first sub objective is establishing a coordinate system with respect to the intermediate fixture. The intermediate fixture is used for ñpottingò the bone as shown in Figure 9. The second sub objective is to determine the rotational and translational transformations on the five axis positioner which will orient and position the bone stock against the disc. The third sub objective is to determine the grid location on the discs for support insertion.

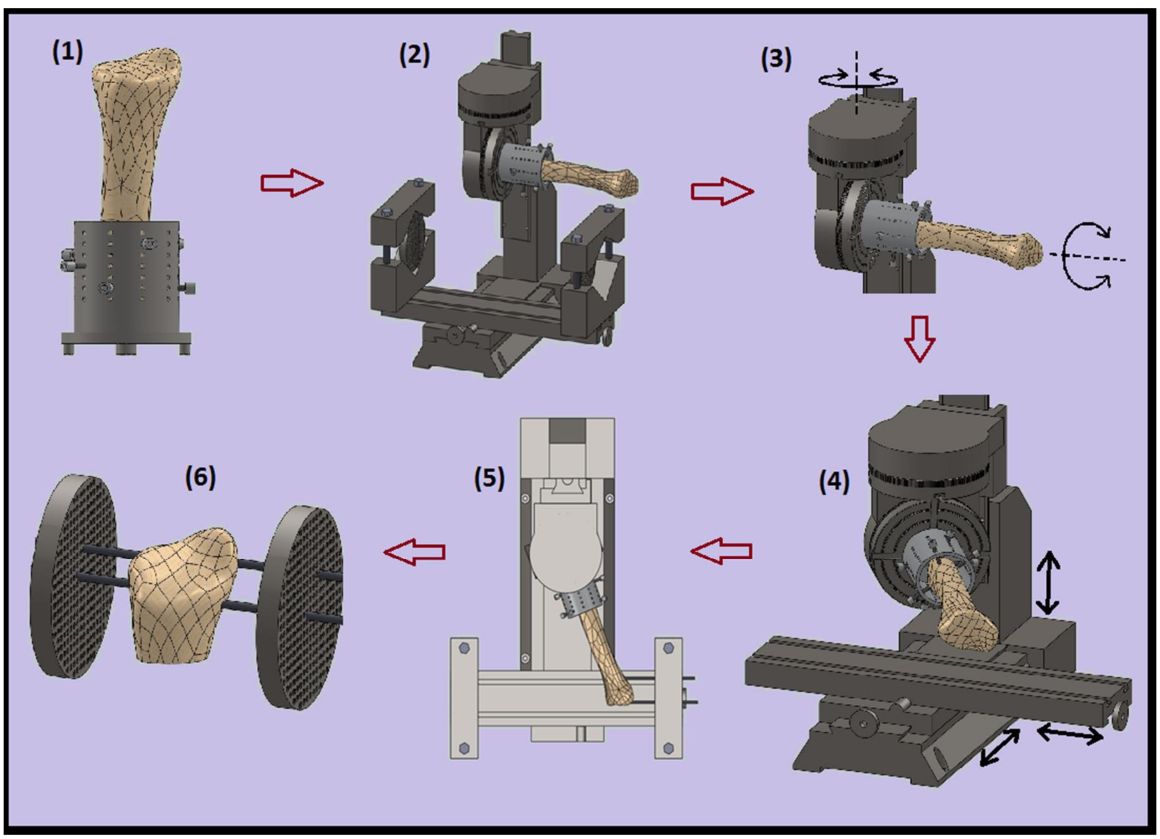

Figure 9 Steps for constructing the machining fixture

Algorithms have been devised to determine the precise site for harvesting the implant from bone stock by matching bone density. The output of these algorithms is in the form of coordinate points and vectors which defines the location and orientation of the sacrificial support structures. This data serves as the input to the process developed in this thesis work.

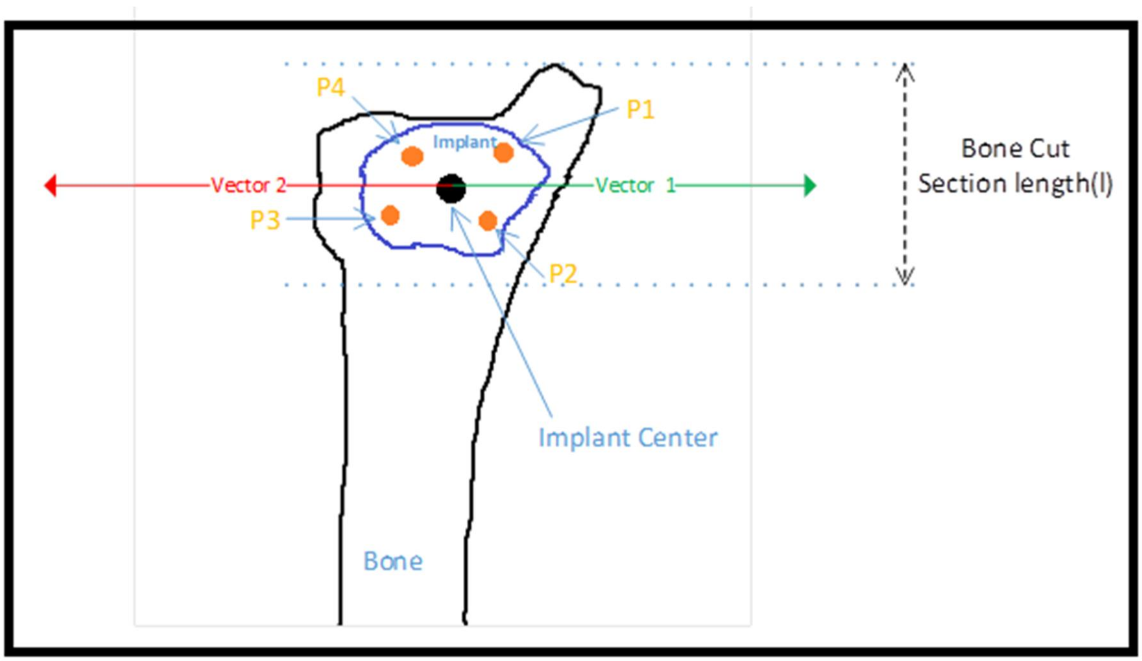

Figure 10 Output of harvesting algorithms

The harvest algorithms output data that comprises of the following:

1. Bone cut section length, l
2. Implant axis. It is defined by two vectors: Vector 1 and Vector 2.
3. Implant Center
4. Location of support structures defined by four points P1, P2, P3 and P4.
5. The distance from the support location to the end of the bone cut section.
6. Depth of the support into the bone

This data is mapped to fixture coordinate systems and the transformations on the five axis positioner are determined using this data. The Denavit and Hartenberg notation gives a standard methodology to write kinematic equations of manipulator [31]. This is specifically useful for serial manipulators where matrices are used to represent the pose (position and orientation) of one body with respect to another. According to their notation, the matrix used to transform a point from frame n to (n-1) is given by

$$P_{n-1} = T_{n-1,n} \cdot P_n = \begin{bmatrix} x_{n-1} \\ y_{n-1} \\ z_{n-1} \\ 1 \end{bmatrix} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_n \\ y_n \\ z_n \\ 1 \end{bmatrix}$$

Denavit and Hartenberg were the first to introduce the spatial transformation between two successive link coordinate systems using 4 X 4 homogeneous coordinate transformation matrix shown above. Paul demonstrated its value for the kinematic analysis of robotic systems in 1981 [32]. The four fundamental transformation matrices using Paul's notation are:

$$Trans(a, b, c) = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad Rot(X, \theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Rot(Y, \theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad Rot(Z, \theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Trans(a,b,c) implies a translation given by the vector $a\hat{i} + b\hat{j} + c\hat{k}$ and Rot(X, θ), Rot(Y, θ) and Rot(Z, θ) imply rotation of θ about the X, Y, Z coordinate axis respectively.

These matrices are extensively used in this thesis to determine transformation matrices for mapping and determining the transformations. There are four major sections in the methodology.

1. Establishing a Coordinate System

2. Mapping data from the Bone Coordinate System to the Fixture Coordinate System

3. Determining the transformations on the five axis positioner

4. Determining the grid locations on the discs for support insertion

3.1 Establishing a Co-ordinate System

The harvesting algorithms make use of the scan data to determine the site of the harvest and the location and orientation of the sacrificial supports. The scanned data has a certain coordinate system and the output of the harvesting algorithms is with respect to this coordinate system. Sometimes it may happen that the origin is located in the virtual space instead of on the work piece body depending on the way of scanning process. Also there is a possibility that the origin gets shifted in the course of preprocessing of the scanned data. Hence it is important to define the coordinate system with respect to a point based on a well-defined feature of the work piece.

Bone stock is anomalous in shape in addition to the variation that exists with the different donors; even though the donated bones might be of the same kind. Hence it is very difficult to pick a feature to define a definite rectangular coordinate system with respect to it that would result in a manufacturing process which is repeatable and reproducible. In such a case the bone can be ñpottedò in an intermediate fixture which has features to define a definite rectangular coordinate system. Also this intermediate fixture can be used to mount the bone to the five axis positioner. The bone potted in the intermediate fixture is shown in Figure 11. Increasing the number of screws in the intermediate fixture, increases the stability of the attachment, but it should be noted that after a certain number of screws adding screws will be redundant.

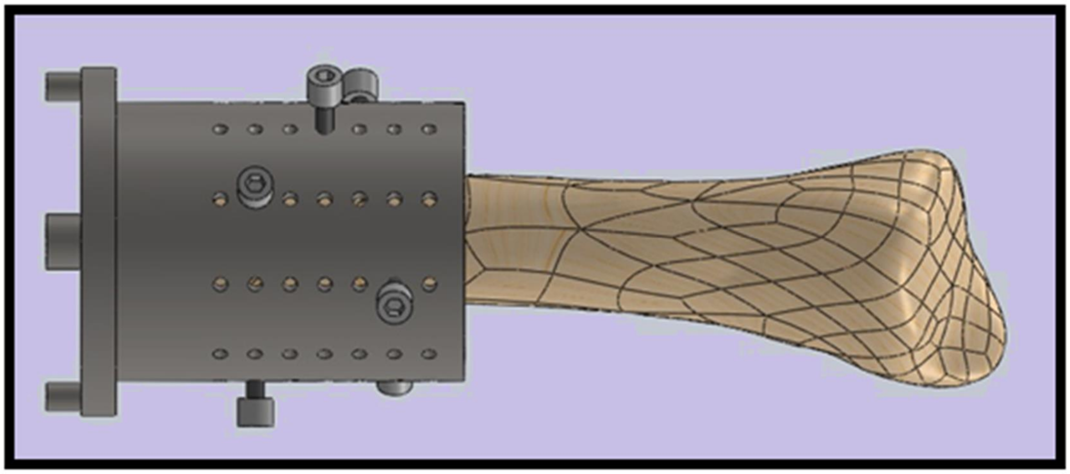

Figure 11 Bone potted in the intermediate fixture

In this section an algorithm has been devised to establish the origin on the desired well defined feature. Establishing the desired coordinate system from the existing coordinate system implies virtual mapping of the data and there is no physical change. A concatenated transformation matrix needs to be developed that accounts for six transformations i.e. a translation and rotation in each of the three axis. And using this matrix, map all the output from the harvesting algorithms to the newly established coordinate system.

$$[T] = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix}$$

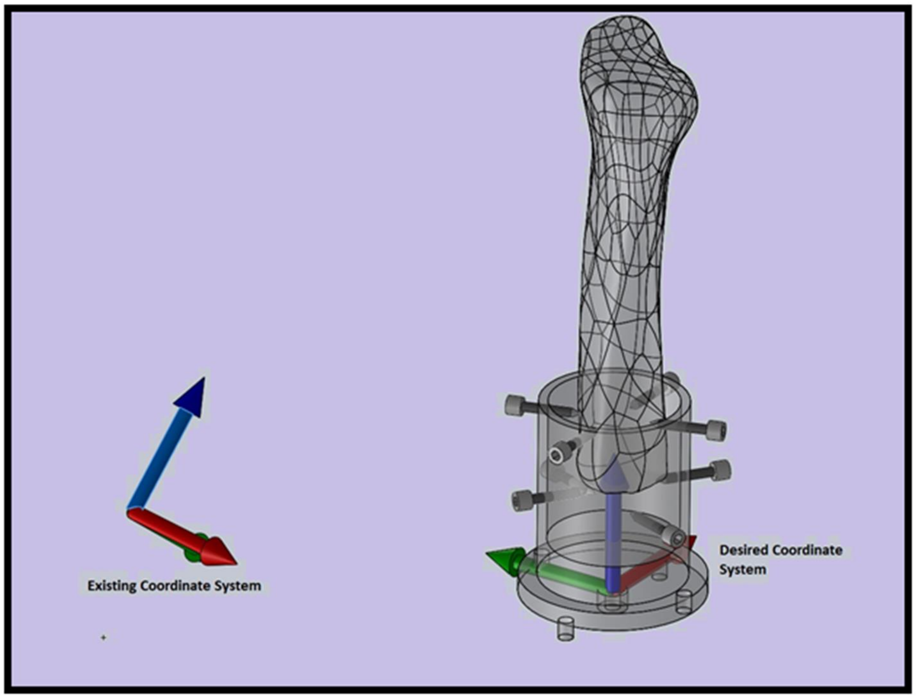

Figure 12 Existing and Desired Coordinate System

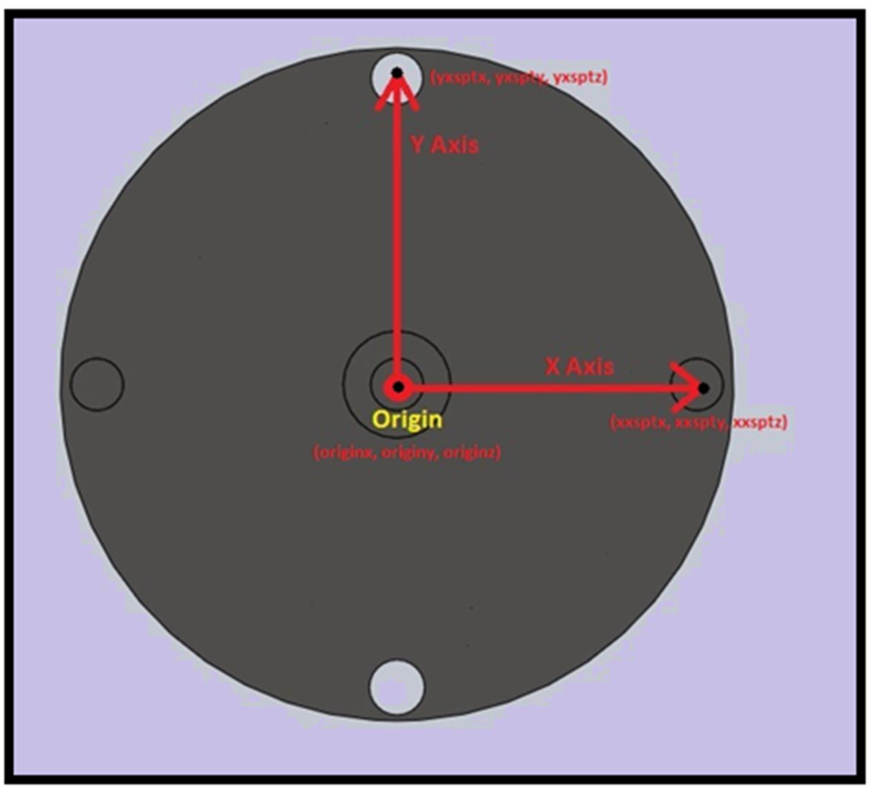

Figure 13 Required points for establishing a new Coordinate System

Once the bone is potted into the intermediate fixture, the next step is to determine from the scan at least three points on the well-defined feature which will form the basis of the desired new coordinate system. The three points are

1. The desired origin, (originx, originy, originz)
2. A point on desired X, (xxsptx, xxspty, xxsptz)
3. A point on desired Y axis, (yxsptx, yxspty, yxsptz)

The center of the extruded cylinder at the center of bottom face of the fixture can be used as the origin, while the center points of the extruded cylinder and the hole on the periphery of the bottom face can be used as points on X-axis and Y-axis. It is critically important to select the points accurately because it will affect the direction of the resulting Z- axis and it should be ensured that it matches with the desired coordinate system.

Using the desired origin and the point on desired X axis, the desired X axis can be defined in a vector form. Similarly using the desired origin and the point on desired Y axis, the desired Y axis can be defined in a vector form. Taking the vector cross product of the desired X axis vector and the desired Y axis vector, the desired Z axis can be determined.

$$\vec{X} = (xxsptx - originx)\hat{i} + (xxspty - originy)\hat{j} + (xxsptz - originz)\hat{k}$$

$$\vec{Y} = (yxsptx - originx)\hat{i} + (yxspty - originy)\hat{j} + (yxsptz - originz)\hat{k}$$

$$\vec{Z} = \vec{X} \times \vec{Y}$$

Let [illegible], [illegible] & [illegible] be denoted by:

$$[illegible] = ([illegible])[illegible] + [illegible] + [illegible]$$

$$[illegible] = ([illegible])[illegible] + [illegible] + [illegible]$$

$$[illegible] = ([illegible])[illegible] + [illegible] + [illegible]$$

The two coordinate systems are: the desired coordinate system, defined by the three vectors [illegible], [illegible] & [illegible] and the existing coordinate system which is in place from the scanner. The objective is to map the harvesting data which is with respect to a coordinate system to the desired coordinate system. Transformation needs to be carried out, in another words the existing coordinate system needs to be moved/matched with the desired coordinate system. Hence the existing coordinate system will be referred to as transitory coordinate system (TCS), because it is moving, while the desired coordinate system will be referred to as the stationary coordinate system (SCS). The next goal is to determine transformation consisting translation distances and rotation angles of the three axes to match the transitory to stationary coordinate system. The first step is to match the origins irrespective of the direction of the axes.

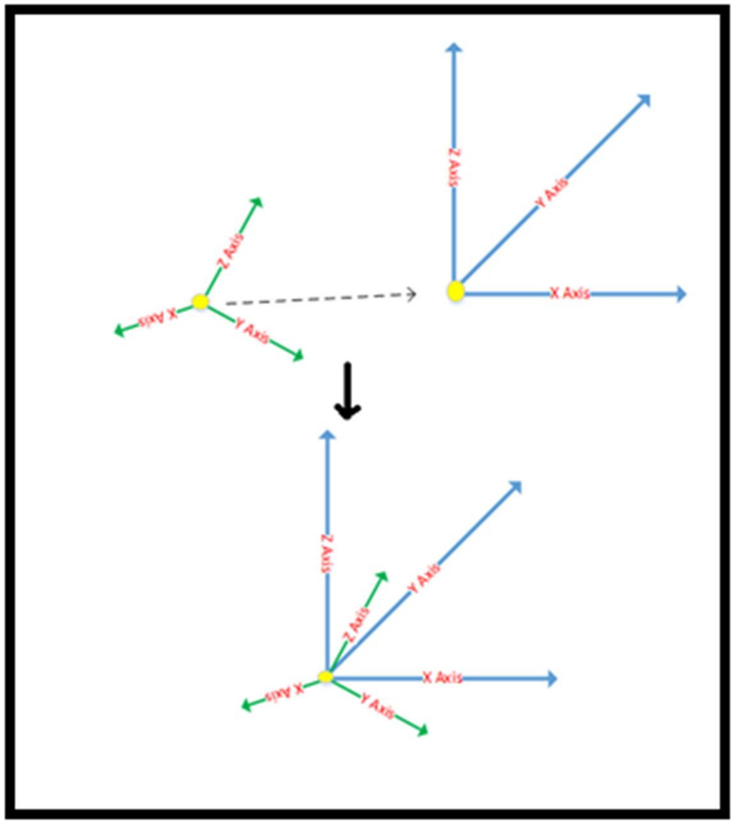

Figure 14 Matching the origins of the two coordinate systems

The Coordinates of the desired origin gives us the translation distances in the each of the three axes to match the origin.

[illegible]

Once the point of origin is matched, the next objective is to match the directions of the axes. In order to match the directions, rotation angles in the three directions are needed to be determined. The rotation angle is determined by calculating the angle between the shadow of the transitory axis vector on the principal plane of the stationary coordinate system perpendicular to the axis of rotation and the corresponding stationary axis. These rotation angles will help forming individual rotation matrices which can be combined to form the final rotation matrix.

In order to match the direction of the first axis, rotations in the other two axes is required. For example, if the Z axis is decided to be matched first then rotation in the X and Y axes of the stationary coordinate system is required. Considering the rotation of the Y axis first, take the shadow of the Z axis vector of TCS on the XZ plane of the SCS and its angle with the Z axis of the of SCS is found. It is denoted by □□□ and is the angle by which the Y axis needs to be rotated.

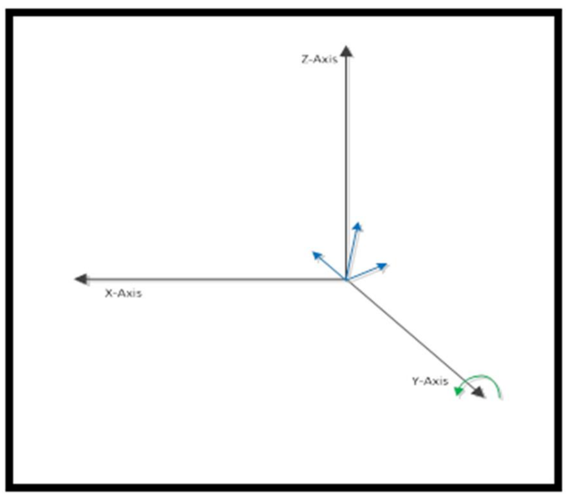

Figure 15 Rotation Y Axis

The magnitude of the angle can be calculated as follows

$$\square\square\square\ \square\ \cos^{\square\square}\square\frac{\square\square\square\square\square}{\sqrt{\square\square\square\square\square^{\square}\ \square\ \square\square\square\square\square^{\square}}}\square$$

Knowing the magnitude of the angle is not enough, the sense of rotation should also be known i.e. should the axis be rotated clockwise or counter clockwise. The sense of rotation is obtained by checking the ôXô direction cosines of the z-axis vector of the TCS:

- If the "X" direction cosine is negative then the rotation will be counter clockwise and the rotation matrix will be

$$R_{y}(\theta_1) = \begin{bmatrix} \cos(\theta_1) & 0 & \sin(\theta_1) \\ 0 & 1 & 0 \\ -\sin(\theta_1) & 0 & \cos(\theta_1) \end{bmatrix}$$

If the "X" direction cosine is positive then the rotation will be clockwise and the rotation matrix will be

$$R_{y}(\theta_1) = \begin{bmatrix} \cos(\theta_1) & 0 & -\sin(\theta_1) \\ 0 & 1 & 0 \\ \sin(\theta_1) & 0 & \cos(\theta_1) \end{bmatrix}$$

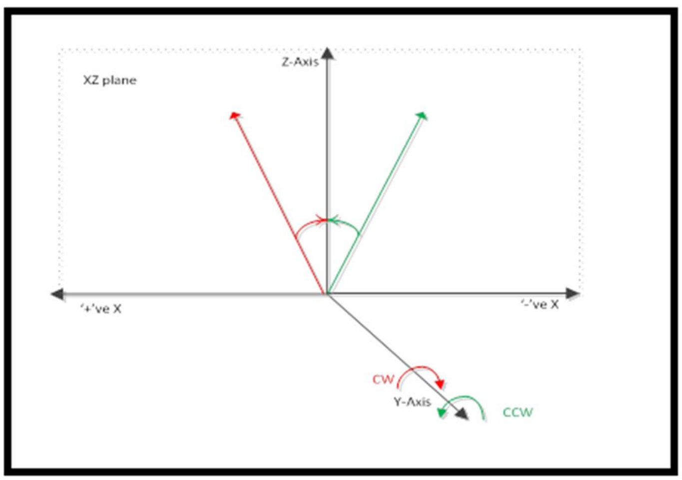

Figure 16 Sense of rotation Y Axis

After this rotation the state of the Transitory Coordinate System can be defined as:

$$[\square] = \begin{bmatrix} \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \end{bmatrix} = [\square\square\square 1] \times \begin{bmatrix} \square\square\square\square\square \\ \square\square\square\square\square \\ \square\square\square\square\square \end{bmatrix}$$

$$[\square] = \begin{bmatrix} \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \end{bmatrix} = [\square\square\square 1] \times \begin{bmatrix} \square\square\square\square\square \\ \square\square\square\square\square \\ \square\square\square\square\square \end{bmatrix}$$

$$[\square] = \begin{bmatrix} \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \\ \square\square\square\square\square 1 \end{bmatrix} = [\square\square\square 1] \times \begin{bmatrix} \square\square\square\square\square \\ \square\square\square\square\square \\ \square\square\square\square\square \end{bmatrix}$$

Once the appropriate matrix is selected and applied then the transitory Z axis vector now lies in the YZ plane of the SCS. The next step is to rotate the X axis of the SCS so that the transitory Z axis lines up with stationary Z axis. The magnitude of the angle is determined by

$$\square\square\square = \cos^{\square\square}\left(\frac{\square\square\square\square\square 1}{\sqrt{\square\square\square\square\square 1^{\square} + \square\square\square\square\square 1^{\square}}}\right)$$

Again the sense of rotation needs to be determined.

- If the ôYô direction cosine (zvecy1) is negative then the rotation will be counter clockwise and the rotation matrix will be

$$[\square\square\square 2] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\square\square\square) & -\sin(\square\square\square) \\ 0 & \sin(\square\square\square) & \cos(\square\square\square) \end{bmatrix}$$

- If the ôYô direction cosine (zvecy1) is positive then the rotation will be r clockwise and the rotation matrix will be

$$[\square\square\square 2] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\square\square\square) & \sin(\square\square\square) \\ 0 & -\sin(\square\square\square) & \cos(\square\square\square) \end{bmatrix}$$

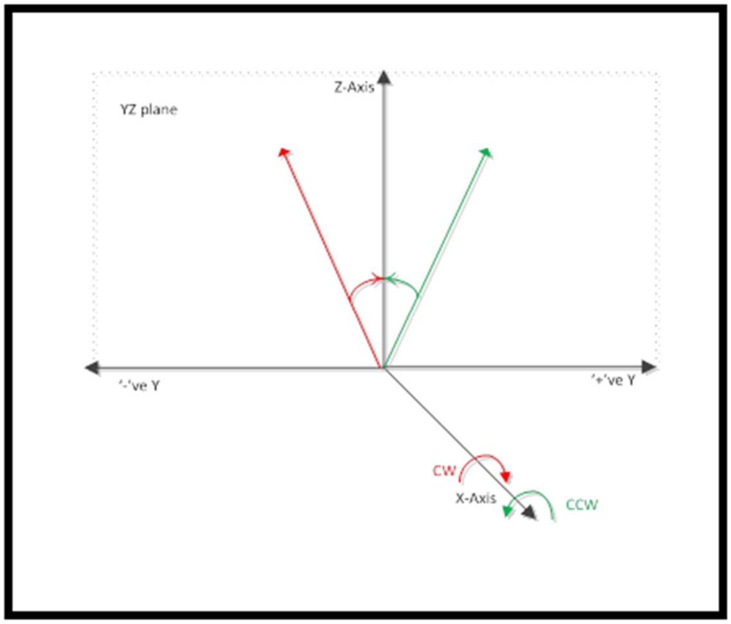

Figure 17 Sense of rotation X-Axis

After this rotation the state of Transitory Coordinate System can be defined as:

The last operation aligned the TCS Z axis to the SCS Z axis completely. Next goal is match the transitory X and Y axis to stationary X and Y axis. The stationary Z axis needs to be rotated to match the other two axes.

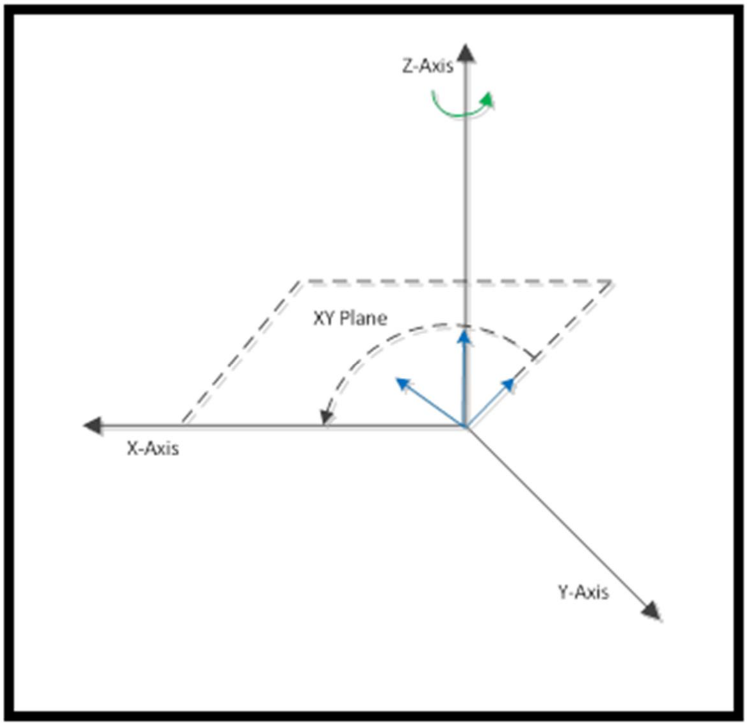

Figure 18 Rotation Z-axis

The angle between the transitory X axis and stationary X axis gives the magnitude of the angle to be rotated and it is calculated as follows:

$$\text{[illegible]} = \cos^{\text{[illegible]}} \frac{\text{[illegible]}2}{\sqrt{\text{[illegible]}2^{\text{[illegible]}} \text{[illegible]} \text{[illegible]}2^{\text{[illegible]}}}}$$

The sense of rotation is obtained by checking the ôYô direction cosines of the desired x-axis vector:

- If the ôYô direction cosine is negative then the rotation will be counter clockwise and the rotation matrix is given by

$$\text{[illegible]}3\text{[illegible]} = \begin{bmatrix} \cos\text{[illegible]} & \text{[illegible]}\sin\text{[illegible]} & 0 \\ \sin\text{[illegible]} & \cos\text{[illegible]} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- If the ôYô direction cosine is positive then the rotation will be clockwise and the rotation matrix is given by

$$[R3] = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ \pm\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

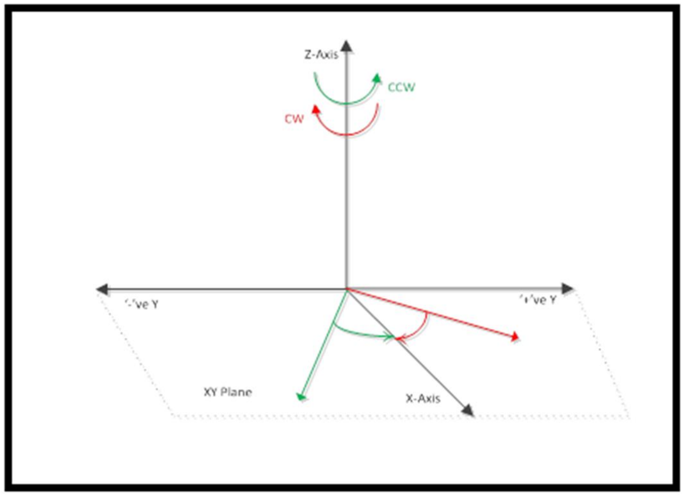

Figure 19 Sense of rotation Z axis

The combining all the rotation matrices will result in the final concatenated rotation matrix [R]. Since matrix multiplication is not commutative, it is important to maintain the order of operations. The final rotation matrix [R] is given by:

$$[R] = [R3][R2][R1]$$

$$\begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \pm\sin(\theta) & 0 \\ \mp\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \pm\sin(\theta) \\ 0 & \mp\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & \pm\sin(\theta) \\ 0 & 1 & 0 \\ \mp\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

The values from [R] and [d] can be inserted into the final transformation matrix. The Transformation matrix so created can be used to map the harvesting data to the desired coordinate system which is with respect to a well-defined feature. So any point or the vector (P,Q,R) can be mapped to the desired coordinate system as follows:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

3.2 Mapping data from the Bone Coordinate System to the Fixture Coordinate System

The previous step ensured that the coordinate system is established on a well-defined feature on the stock material. In order to proceed and use the five axis fixture to position and orient the stock (donor bone) to screw in the sacrificial support, the harvest data now needs to be mapped with the fixture coordinate system.

The transformation matrix can be given by:

$$[T] = \begin{bmatrix} Or_{11} & Or_{12} & Or_{13} & S_x \\ Or_{21} & Or_{22} & Or_{23} & S_y \\ Or_{31} & Or_{32} & Or_{33} & S_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} [Or] & [S] \\ 0 & 1 \end{bmatrix}$$

Where [Or] matrix represents the orientation operation whereas the [S] matrix the distance adjustment that need to be done to match the two origins. The distance in each axis i.e. Sx, Sy and Sz can be accurately determined by an accurate device like FARO arm (articulated CMM).

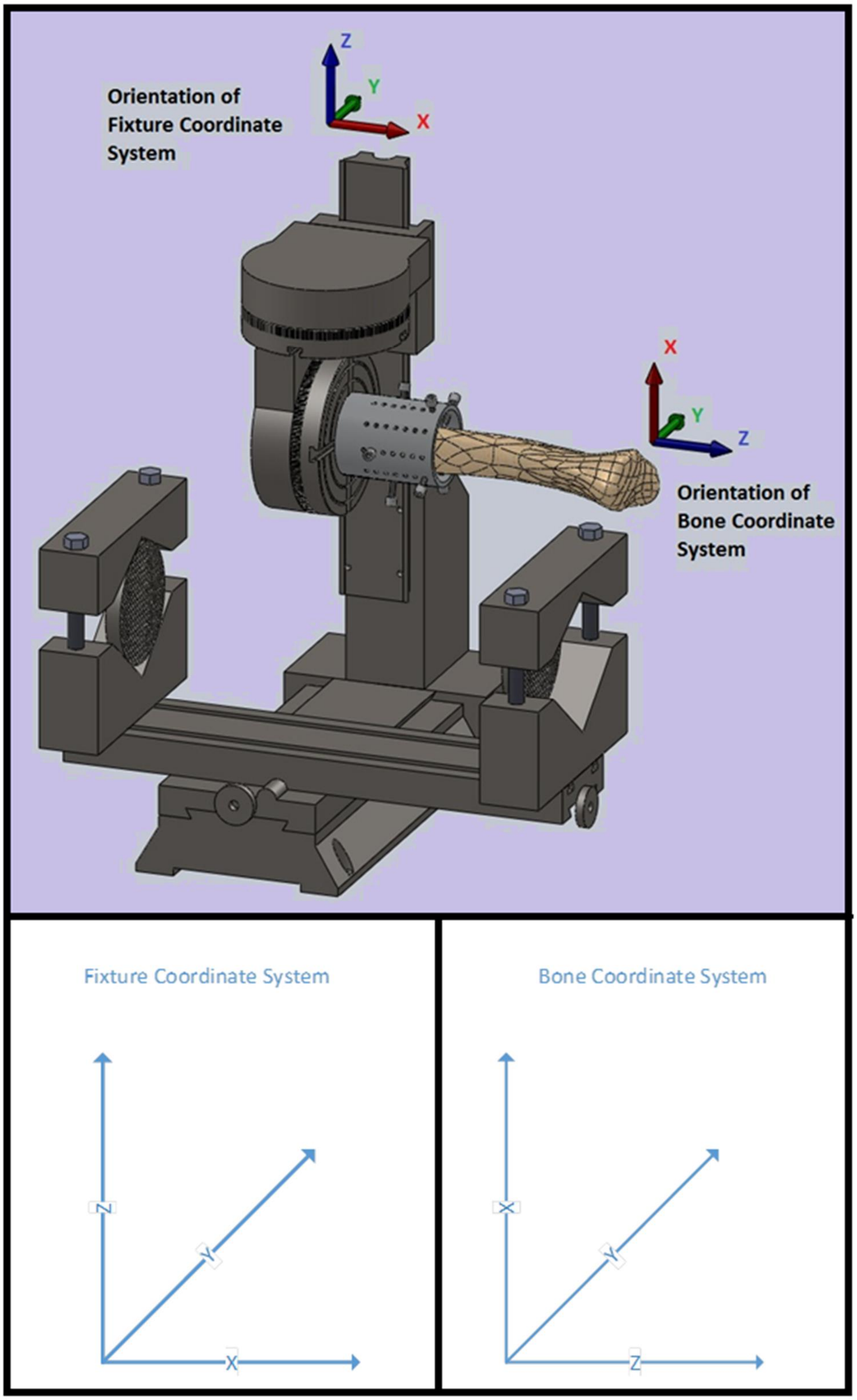

Figure 20 Mapping from Bone to Fixture Coordinate System and their orientations

In the current scenario, it can be observed that the two coordinate systems have same Y axis and the other two axes are exchanged, so the resulting orientation matrix will be:

$$[Or] = \begin{bmatrix} Or_{11} & Or_{12} & Or_{13} \\ Or_{21} & Or_{22} & Or_{23} \\ Or_{31} & Or_{32} & Or_{33} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

The operation for converting (X,Y,Z) coordinate of the harvesting data to the (X′,Y′,Z′) coordinate of the fixture coordinate system is nothing but multiplying the transformation matrix [Or] to the coordinates of the Bone Coordinate system as shown below.

$$\begin{bmatrix} X' \\ Y' \\ Z' \\ 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & t_x \\ 0 & 1 & 0 & t_y \\ 1 & 0 & 0 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

3.3 Determining the transformations on the five axis positioner

After mapping the harvesting data in the fixture coordinate system, now the bone stock is ready to be oriented and positioned using the five axes positioner.

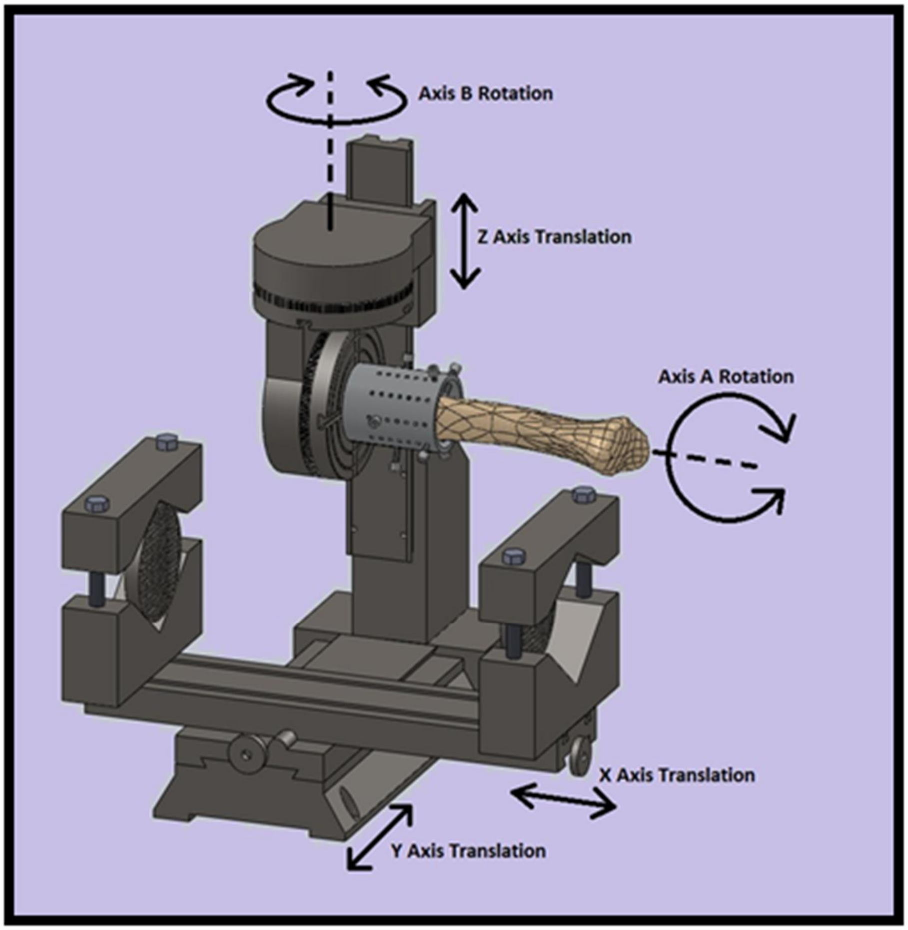

Figure 21 Rotations and Translations on the five axis positioner

The bone stock needs to be positioned such that the sacrificial supports can be screwed into the implant site in the bone. The sacrificial support screws are parallel to the axis of the implant and by default are parallel to the axis formed by joining the centers of the disk. The objective of this section is to position the bone stock such that the axis of the implant is coincident with the axis formed by joining the centers of the disk.

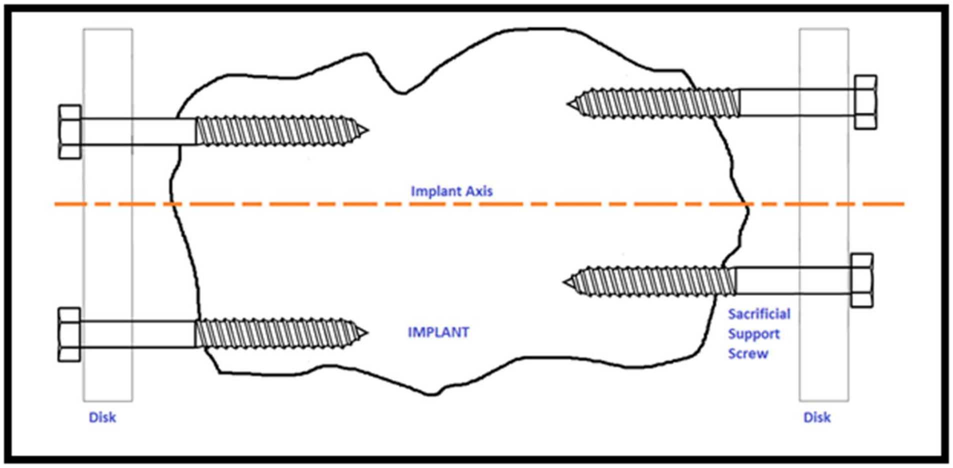

Figure 22 Sacrificial supports parallel to implant axis

The axis of the implant is given in the vector form from the harvesting algorithm. Two vectors (Vector 1 and Vector 2) in opposite direction define the axis of the implant. The first step is to select the direction of the axis to derive the angle of rotation in two axes. The goal is to select the vector which makes a smaller angle with the X axis of the fixture coordinate system.

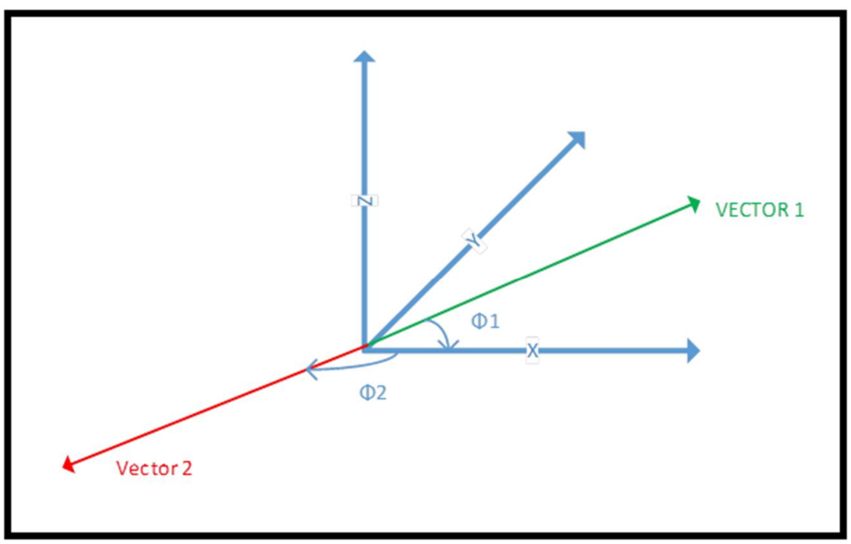

Figure 23 Angles made by the two vectors

The two vectors are represented as

$$\text{Vector 1: } x_1\hat{i} + y_1\hat{j} + z_1\hat{k}$$

$$\text{Vector 2: } x_2\hat{i} + y_2\hat{j} + z_2\hat{k}$$

The vector that makes the smallest angle with the X axis is to be selected. Let vector 1 make ū 1 with the X axis and let vector 2 make ū 2 with the X axis. These angles can be calculated as follows:

$$\theta_1 = \cos^{-1}\left(\frac{x_1}{\sqrt{x_1^2 + y_1^2 + z_1^2}}\right)$$

$$\theta_2 = \cos^{-1}\left(\frac{x_2}{\sqrt{x_2^2 + y_2^2 + z_2^2}}\right)$$

Comparing angles ū 1 and ū 2, the vector can be selected. In a way it implies that the vector existing in a quadrant defined by +ve X axis is selected. The quadrant shown in green represents the ones defined by +ve X axis.

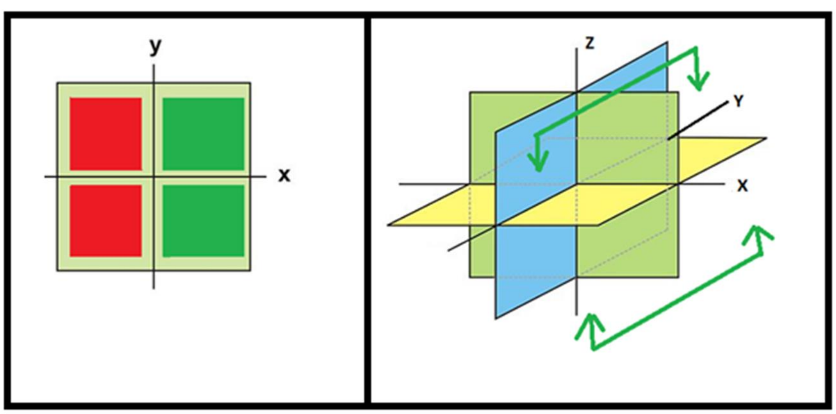

Figure 24 Selected quadrants

Clearly in the case shown vector 1 makes smaller angle with the X axis and is selected.

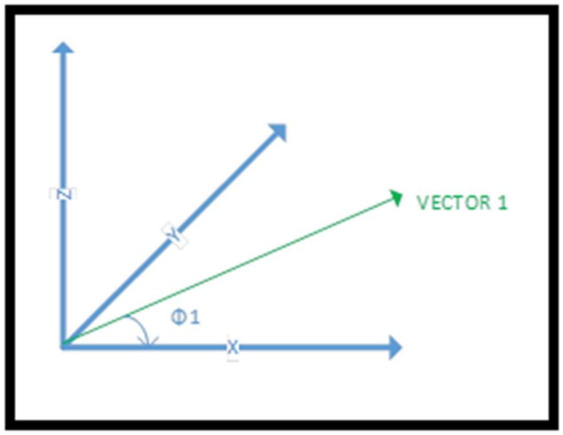

Figure 25 Selected vector

Due to the physical limitation of the rotation axis of the positioner, another case needs to be considered before proceeding. The construction of the positioner is such that it limits a complete 360° rotation of the axis B. It is only able to provide a rotation of 210°. It is important at this stage and necessary to take this into account because the algorithm should not output a solution which will result in faulty transformations. The ability of rotation of Axis B is shown in the following figure:

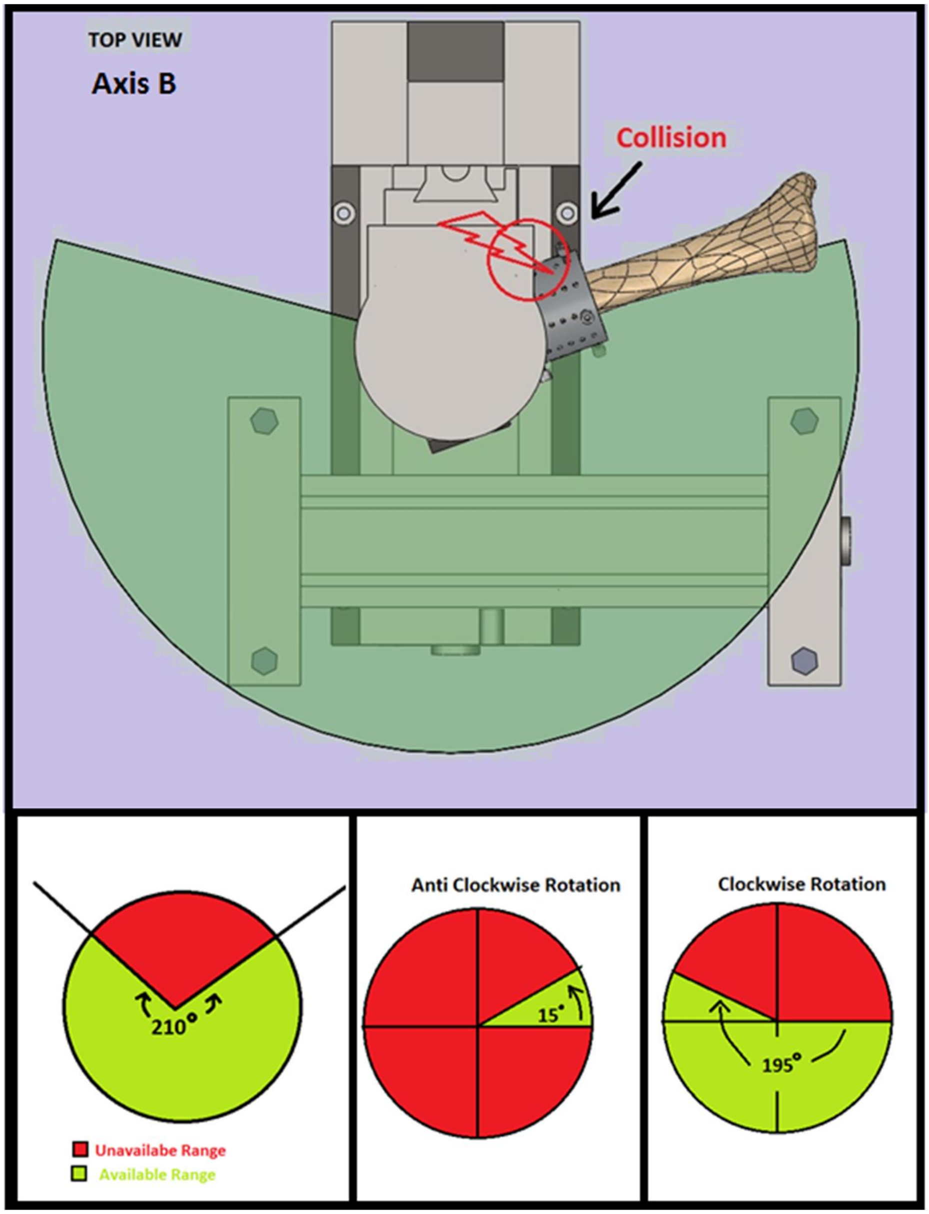

Figure 26 Limitation of axis B

As it can be observed from the figure that axis B offers 195° of rotation in clockwise sense. If a Vector lies in the quadrants [+X, +Y, +Z] or [+X, +Y, -Z], then it can easily be rotated such that it becomes perpendicular to the YZ plane. The maximum rotation would be 90° and the available rotation is 195°, which is way more than what is required. Also axis B has only 15° available for rotation in counter clockwise sense. So, if a vector makes an angle greater than 15° in quadrants [+X, -Y, +Z] and [+X, -Y, -Z] then the resulting transformation will be faulty because the user would not able to rotate Axis B. One of the solutions for this case is to flip the entire set of solution from harvesting algorithm by 180° around X axis. With the 180° flip, the vector will now lie in the available range for rotation in axis B. It is important to note that not only the vectors defining the axis of the bone implant are flipped but the entire set is flipped which includes the stock bone.

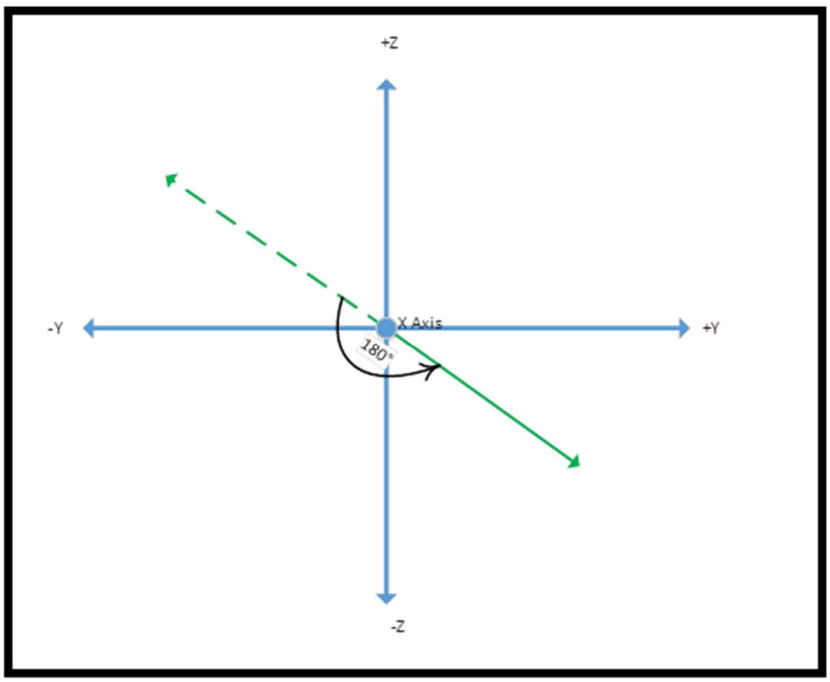

Figure 27 Flipping the vector

The selected vector is denoted as:

[illegible]

The next step is to use the selected vector ([illegible]) for calculating the rotations in Axis A and Axis B such that it becomes perpendicular to the YZ plane (the face plane of the disks).

The first rotation under consideration is that of axis A and coincides with the X axis and this rotation will make the selected vector (⍰) lie in the XY plane. In order to calculate the magnitude of rotation, the shadow of the selected vector on the YZ plane (or a Plane parallel to YZ plane) needs to be considered.

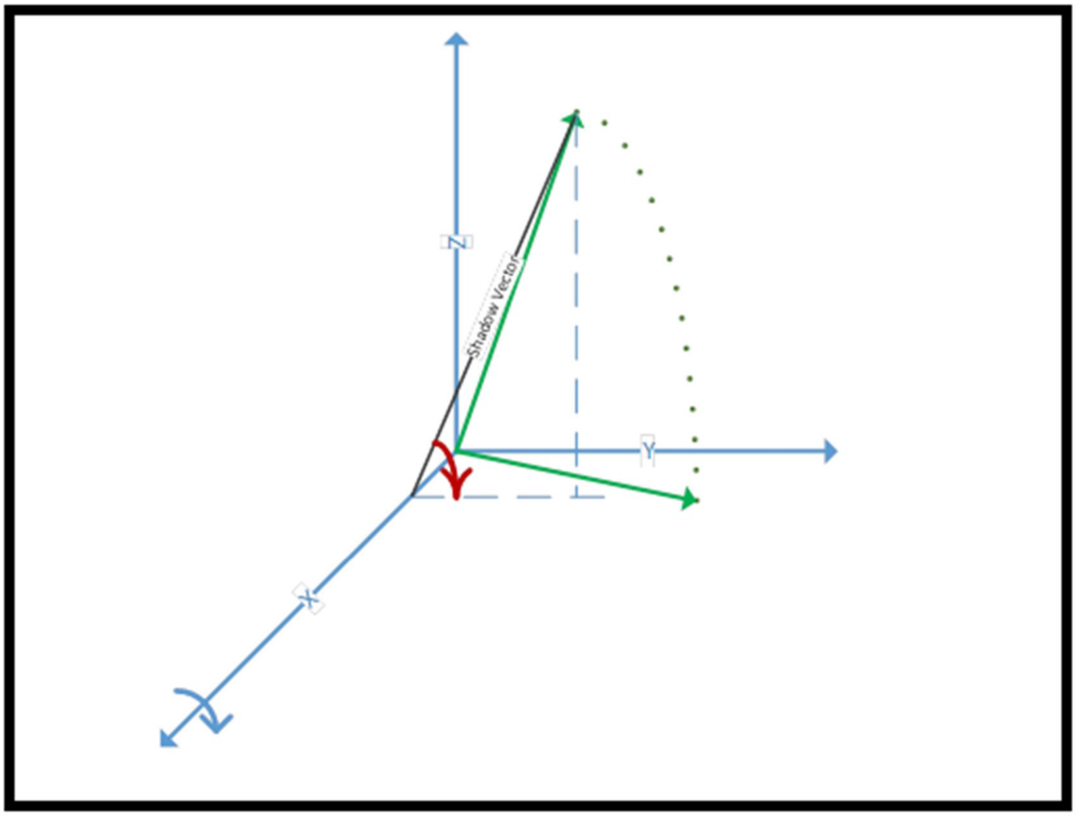

Figure 28 Axis A rotation

Let the angle made by the shadow vector or the horizontal be "α" (alpha). It's shown red in the figure. The angle "α" can be calculated as follows:

$$\alpha = \cos^{-1}\left(\frac{b}{\sqrt{b^2 + c^2}}\right)$$

Once magnitude of the angle of rotation is known, the next step is to determine the sense of rotation. The goal in this step is to make the selected vector lie in the XY plane. As discussed earlier there are four quadrants under consideration and the rotation associated with each quadrant can be understood from Figure 29

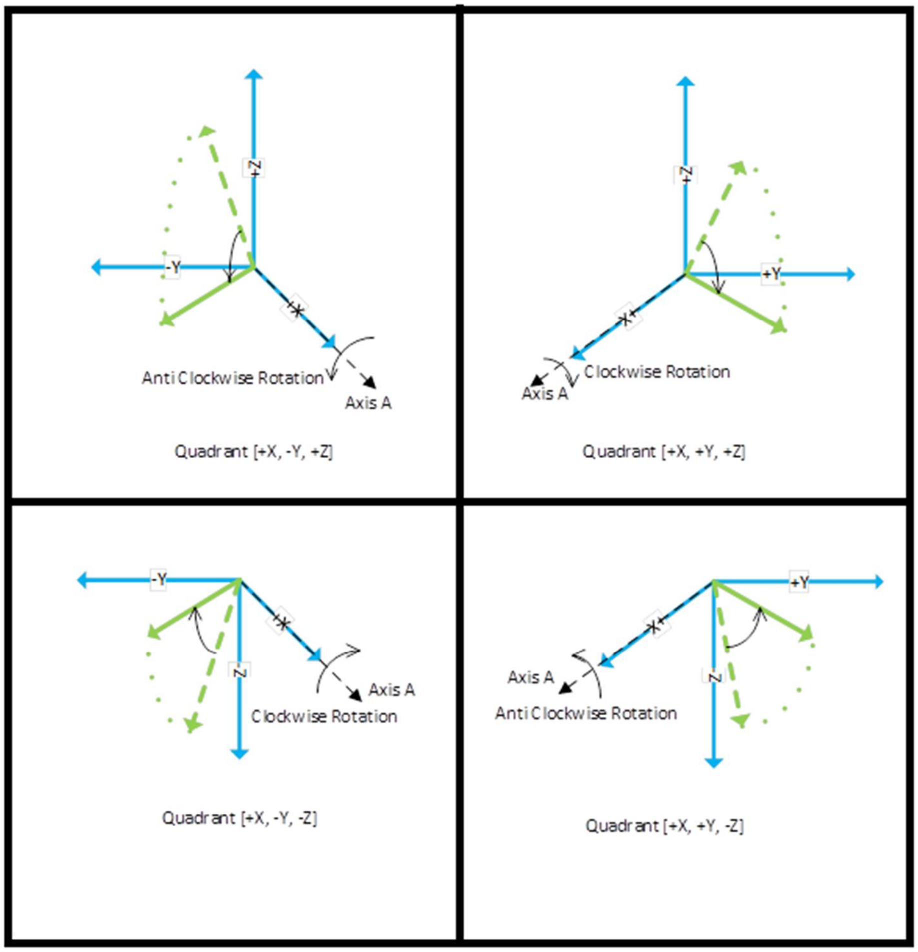

Figure 29 Sense of rotation for axis A

It can be noticed that for quadrants [+X, -Y, +Z] and [+X, +Y, -Z] the rotation for Axis A is anti-clockwise and the rotation matrix denoted by [Mat1] will be given as

$$[Mat1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{bmatrix}$$

Similarly it can be noticed in the case of quadrants [+X, +Y, +Z] and [+X, -Y, -Z] the rotation for Axis A is clockwise and the rotation matrix in this case denoted by [Mat1] will be given as

$$[\square\ \square\square 1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\square) & -\sin(\square) \\ 0 & \sin(\square) & \cos(\square) \end{bmatrix}$$

Once the magnitude of the angle is calculated and the sense of rotation is determined then Axis A is rotated on the fixture with this input. After the rotation, the selected vector ($\square$) now lies in the XY plane and its component change as follows:

$$\square\square\square = \begin{bmatrix} \square\square \\ \square\square\square \\ \square\square \end{bmatrix} = [\square\ \square\square 1] \times \begin{bmatrix} \square \\ \square\square \\ \square \end{bmatrix}$$

With the multiplication of [Mat1] to the vector ($\square$), the Z directional cosine (ca) of this vector will be zero as the vector now lies in the XY plane. The [Mat1] is used to transform reamainder of the harvest data as well.

The next step is to determine the angle rotation of Axis B. The Axis B coincides with the negative Z axis of the fixture. Let this angle of rotation be denoted by β. This rotation step will make vector ($\square$) perpendicular to the YZ plane and the vector ($\square$) will coincide with the X axis. The magnitude β can be determined by the following equation

$$\beta = \cos^{\square\square}\left(\frac{aa}{\sqrt{aa^{\square} + bb^{\square}}}\right)$$

The next step is to determine the sense of rotation of Axis B. It can be understood from the Figure 30. In a simple sense it can be said that if the ôYô directional cosine of vector (⍰) is positive then Axis B is to be rotated clockwise and if the "Y" directional cosine of vector (⍰) is negative then Axis B is to be rotated anti clockwise.

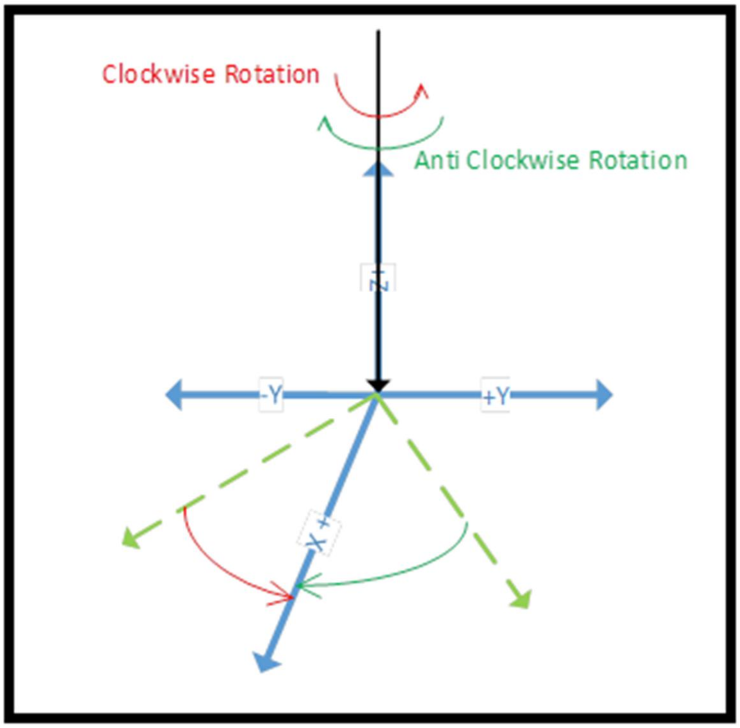

Figure 30 Sense of rotation for axis B

Let the rotation matrix of axis B be denoted by [Mat2]. For a clockwise rotation is represented as:

$$[Mat2] = \begin{bmatrix} \cos(\theta_2) & \sin(\theta_2) & 0 \\ -\sin(\theta_2) & \cos(\theta_2) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

And the anti-clockwise rotation of the axis B is represented as:

$$[Mat2] = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 \\ \sin(\theta_2) & \cos(\theta_2) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The positioner is rotated with this input and the vector (⍰) is now perpendicular to the YZ plane and the resulting cosines will be as follows:

[illegible]

It should be noted that since the vector ([illegible]) is perpendicular to the YZ plane now, the Y and the Z directional cosine of the vector bb and cb respectively will become zero after this step. Similar to the previous step the [Mat2] is used to transform the harvest data to current position.

The rotation transformations oriented the stock bone and now the next step is to position the bone by determining the translation transformation in each of the three axes. The harvesting data consists of a coordinate point known as Implant center through which the axis of the implant defined by vector 1 and vector 2 passes. This is shown in the following figure:

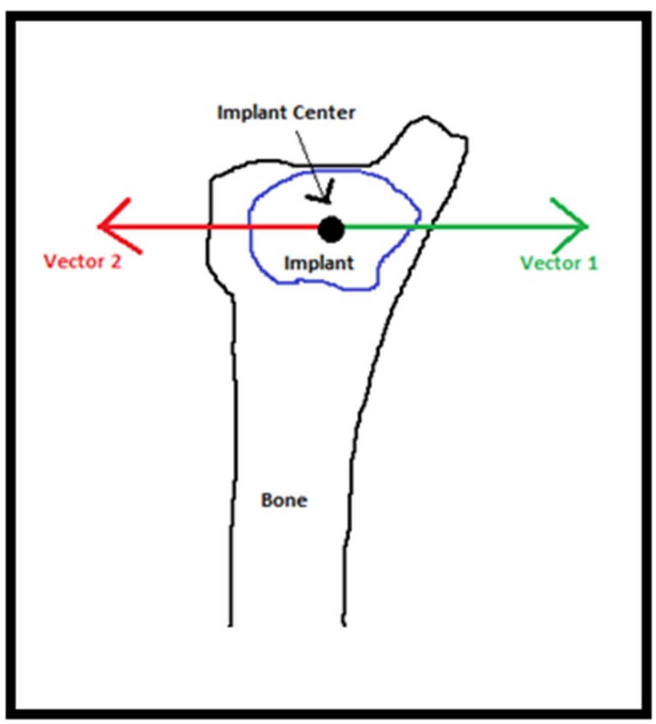

Figure 31 Implant center on the axis of rotation

To determine the translation distances in each of the individual axis, the implant center denoted by the (icx, icy, icz) is used. The center of disk 1 is known, it can be determined using a CMM machine and the value of the coordinates can be recorded and saved. Let the center of the disk be denoted by the (dskx, dsky, dskz). Let the translation distance in X, Y and Z axis be denoted by Px, Py and Pz respectively. These can be defines as

⍰⍰ ⍰ ⍰⍰⍰⍰ ⍰ ⍰⍰⍰ ⍰ ⍰

⍰⍰ ⍰ ⍰⍰⍰⍰ ⍰ ⍰⍰⍰

⍰⍰ ⍰ ⍰⍰⍰⍰ ⍰ ⍰⍰⍰

Where, ⍰ is the distance the bone stock needs to be positioned away from the disk. At the same distance disc 2 can be positioned from the bone.

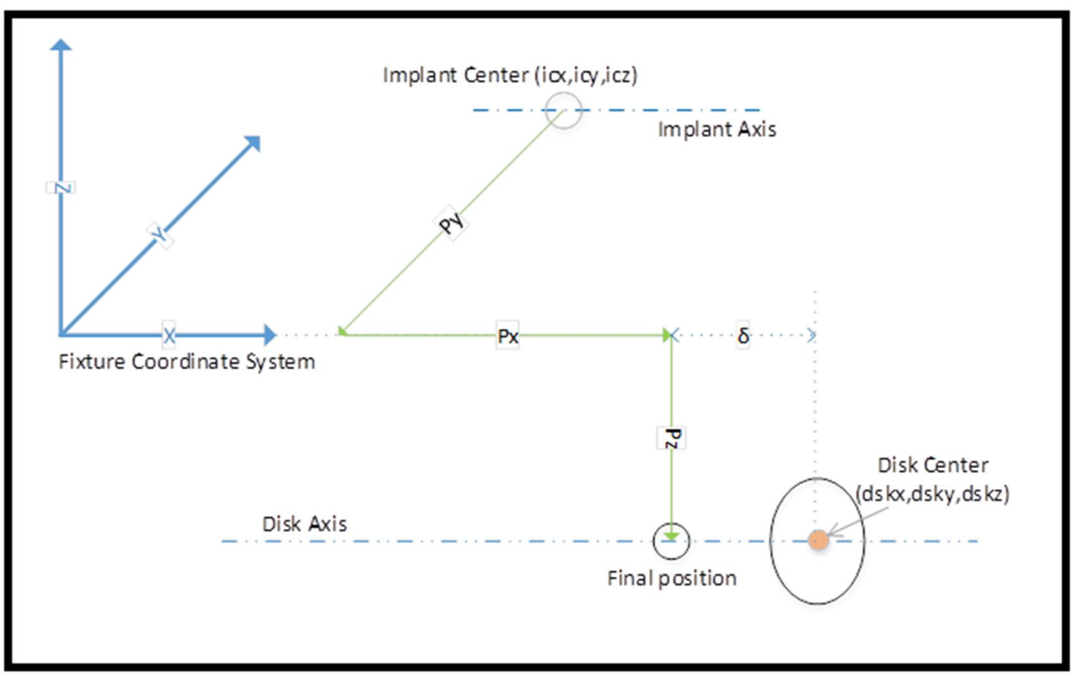

Figure 32 Translations in three axes

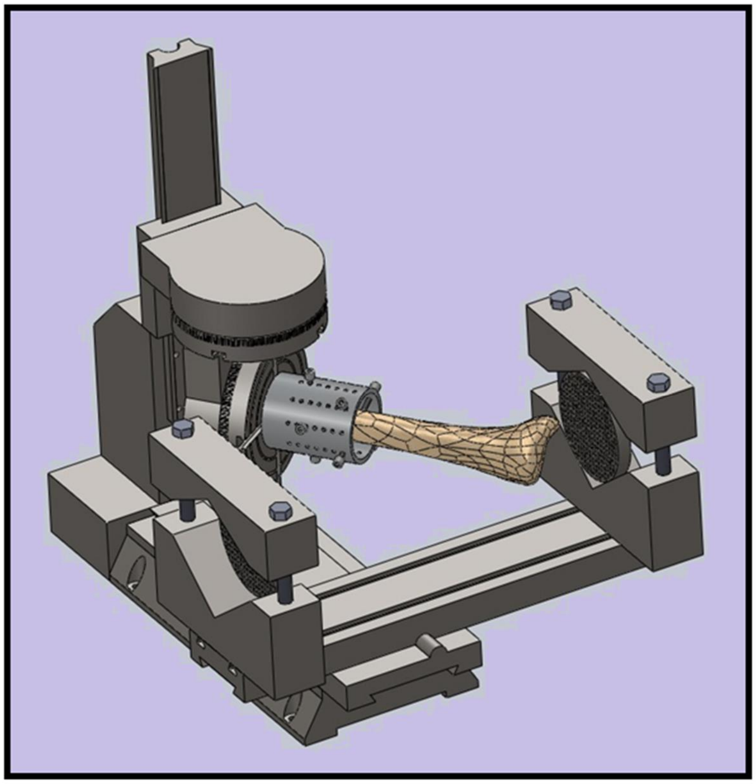

Figure 33 Setup after transformation

3.4 Determining the grid locations on the discs for support insertion

Once the bone stock is oriented and positioned in the final position, the next step is to insert the sacrificial supports. The sacrificial supports have to be inserted in a specific location. The harvesting algorithm outputs the location of the sacrificial support in the form of four coordinate points P1, P2, P3 and P4. Two supports from each disk; P1 and P2 points are associated with Disk 1 and P3 and P4 are associated with Disk 2.The ideal sequence of operation is: supports from Disk 1 are inserted first, followed by supports from disk 2 and then trimming of the bone stock by the bone cut section length. Depending on the angle of rotation of the axis B, this sequence can change. If the angle of rotation for axis B is less than 45º, then the movement of disc 2 will be restricted. In this case, the sequence of operation is: supports from Disk 1 are inserted first, followed by trimming of the bone stock by the bone cut section length and then supports from disk 2 are inserted.

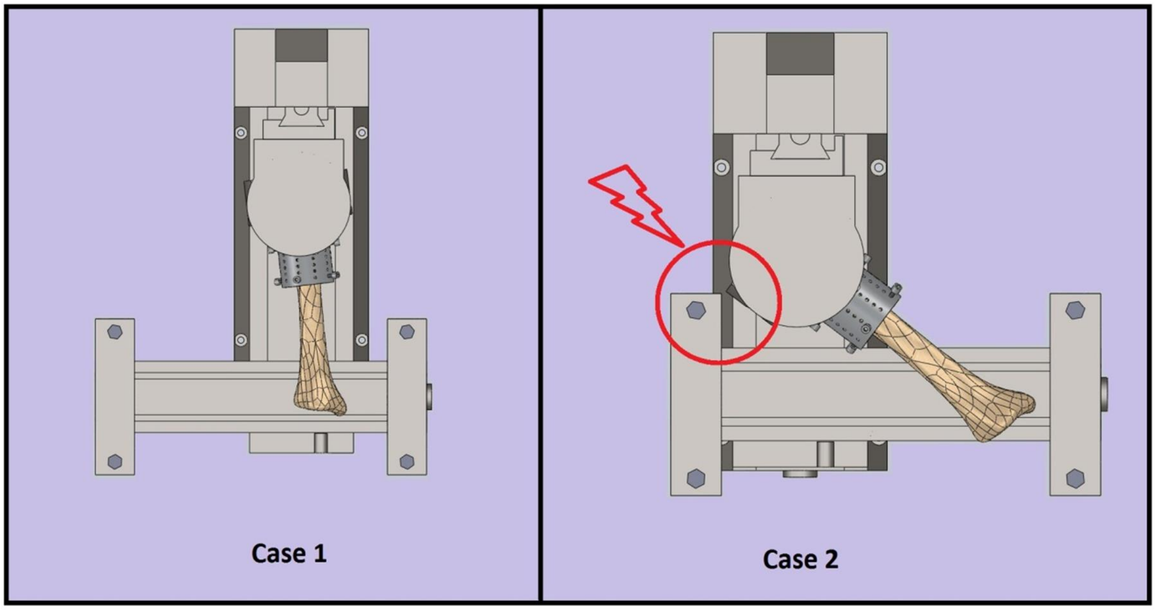

Figure 34 Cases for determining sequence of operation

As discussed in the previous section the center of the disk is (dskx, dsky, dskz). The disk lies in a plane parallel to the YZ plane with respect to the fixture coordinate system. Using the sign conventions of the fixture coordinate system and the center of the disk, it can be divided into four quadrants as shown in the figure. Let ‘k’ be the vertical and horizontal distance between the adjacent holes.

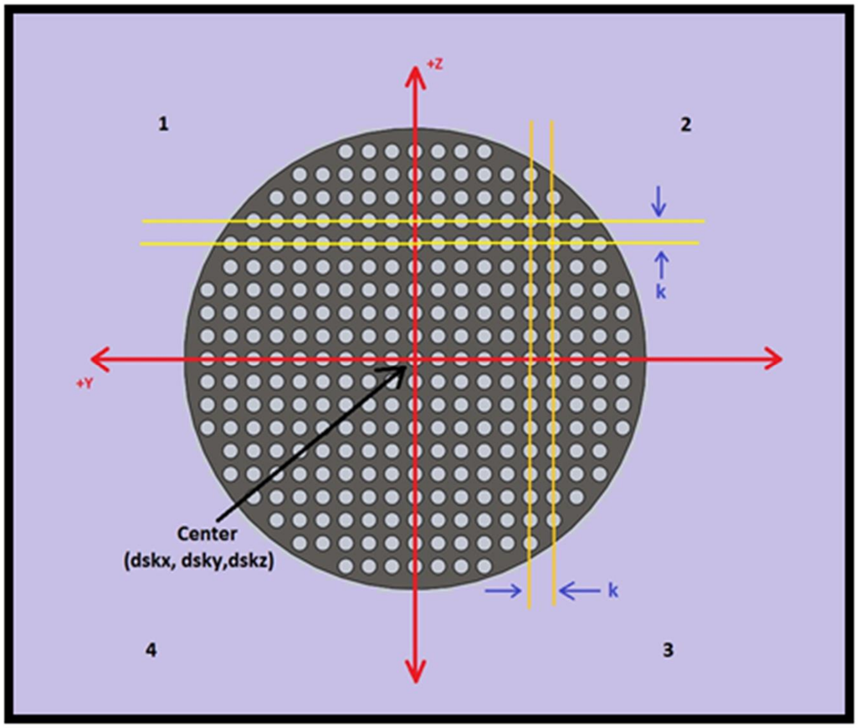

Figure 35 Quadrants on the disc

In order to determine the location of the supports on the grids of Disk 1 and Disk 2 consider the Y and Z coordinates of the support points P1, P2, P3 and P4. Using the transformations in the previous section, the center of the implant and the center of the disks are aligned. The distance of the support points along Y and Z axis from the center of the implant will lead to determining the hole on the disk grid.

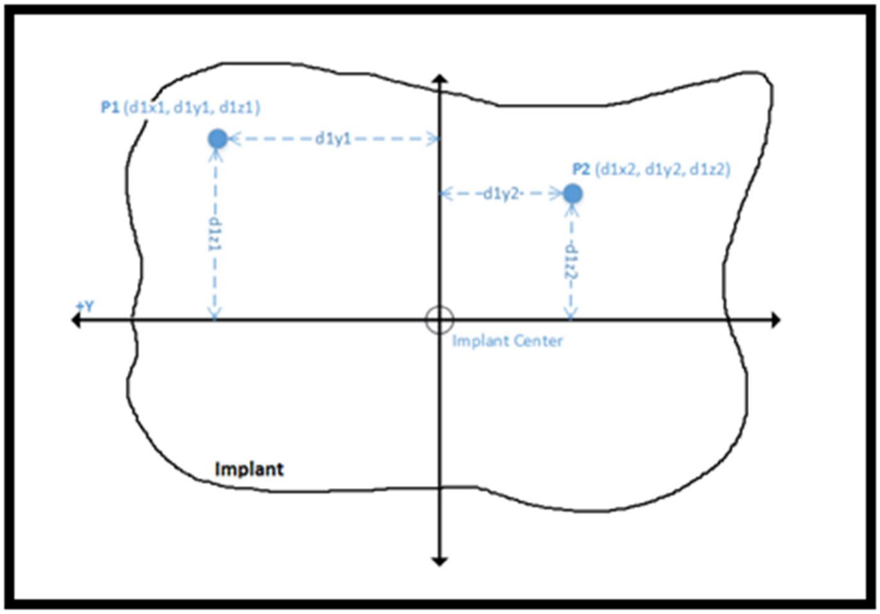

Figure 36 Support Locations on implant's section plane YZ

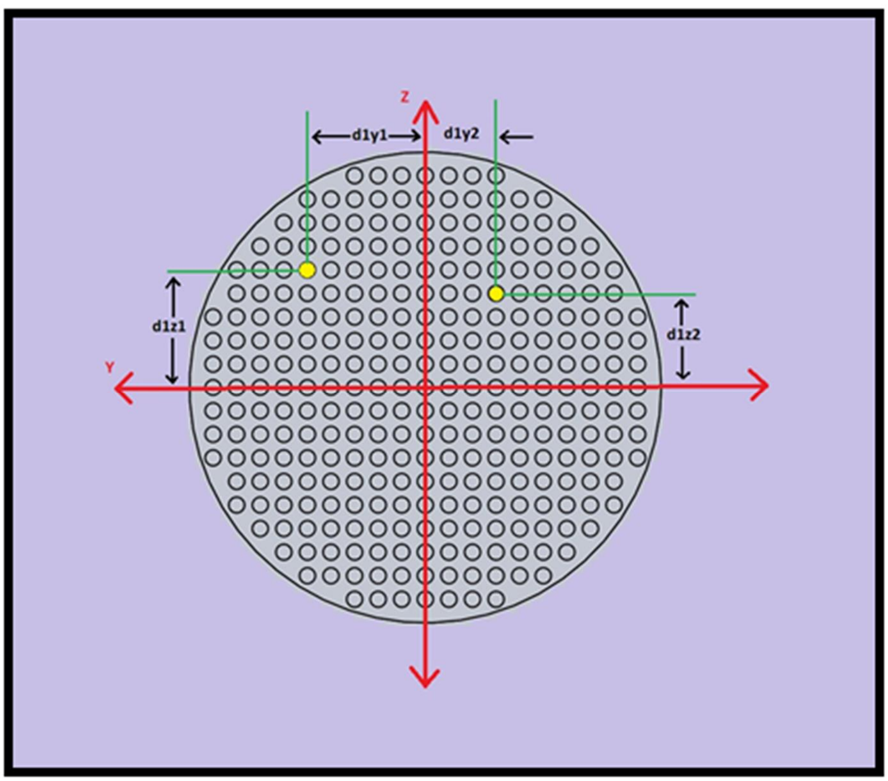

Figure 37 Support locations on the disc

The harvesting algorithm also outputs the depth of the supports. Combining the depth and grid location information the supports can be inserted.

It is important to hold the bone rigidly during support insertion and trimming of the bone stock. Hence a C frame support is utilized to hold the bone stock in place. The C frame is shown in the following figure

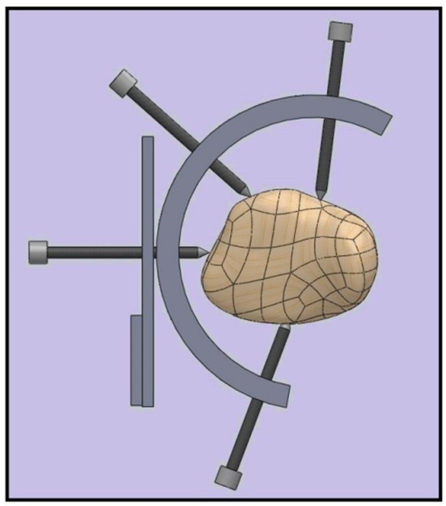

Figure 38 C-frame support

Transferring of the stock to the CNC machine should be done carefully. In order to rigidly hold the disks during transfer, an additional handle can be used. Once the stock is transferred to the CNC machine, it is ready to be machined using tool paths determined by the CNC-RP.

CHAPTER 4: IMPLEMETATION

The necessary functions for the algorithms discussed in the previous sections for calculating transformations were implemented in C/C++ built into a single Microsoft Visual Studio 2012 executable project. Testing was performed using 32-bit PC running windows XP on an Intel Pentium D 3.0 GHz CPU 2 GB of RAM.

The developed executable program takes the output given by the harvesting algorithms as input and solves the equations using this data to give output in the form of translational distances in the three linear axes and rotational angles for the two rotary axes. It also determines the grid locations for inserting sacrificial supports from disc one and disc two.

The following data was obtained as an output from the harvesting algorithms after a suitable implant site was identified along with sacrificial support locations:

Table 2 Input data from harvesting algorithms

Sr. No.	Description	X Coordinate	Y Coordinate	Z Coordinate
1	Implant Center	31.0101	42.0362	145.5340
2	Location of the supports (end point of the support inside of the tibia bone)			
3	P1	22.5168	45.7239	141.810
4	P2	22.3043	40.2761	141.5222
5	P3	17.0727	48.0933	142.6743
6	P4	14.6476	37.1978	142.0983
7	Normal vector for support 1&2	-0.9074	0.3949	0.1440
8	Normal vector for support 3&4	0.9074	-0.3949	-0.1440
9	Distance from p1 to the end of the bone cut section			36.4695 mm
10	Distance from p2 to the end of the bone cut section			37.4695 mm
11	Distance from p3 to the end of the bone cut section			14.4885 mm
12	Distance from p4 to the end of the bone cut section			18.4885 mm

The executable program starts by asking the user if the output data from the harvesting algorithms is with respect to the desired origin i.e. in this case the center of the intermediate fixtureös base is the desired origin. The provided data was not with respect to the desired origin. The program now applies the algorithm discussed in section 3.1 of this thesis and asks the user for coordinates of three points: the desired origin, a point on desired X-axis and a point on desired Y-axis.

Figure 39 Bone potted in the intermediate fixture

These points can be found out by opening the original scan files in CAD software. For the given data the coordinates were found to be as:

Table 3 Desired Coordinate System Data

		X Coordinate	Y Coordinate	Z Coordinate
1	Desired Origin	24.37	41.81	22.90
2	Point on Desired X- Axis	6.78	13.49	23.14
3	Point on Desired Y-Axis	53.43	23.57	17.45

Using these values the rotational angles determined to align the axes of the coordinate systems are as follows

Table 4 Rotation angles for establishing the desired coordinate system

Sr. No.	Axis	Rotational Angle radians	Sense of Rotation
1.	Y	0.137884	Clockwise
2.	X	0.076826	Clockwise
3.	Z	2.121858	Counter Clockwise

The translational distances in each of the axes is simply the three coordinates of the desired origin. This information was used to construct a transformation matrix which would be used to map the data from the harvesting algorithms to the desired bone coordinate system. The transformation matrix obtained from the program is as follows:

$$\begin{bmatrix} -0.527 & -0.849 & -0.007 & -24.37 \\ 0.838 & -0.522 & -0.156 & -41.81 \\ 0.137 & 0.987 & 0.0 & -22.90 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

Applying the transformation matrix, the harvesting data changes to:

Table 5 Data after mapping to Desired Coordinate System

	X Coordinate	Y Coordinate	Z Coordinate
Implant Center	-75.3915	-60.5924	22.8641
P1	-74.0697	-69.0536	25.3421
P2	-69.3320	-66.3426	19.9328
P3	-73.2038	-74.990	26.9360
P4	-63.7292	-69.5688	16.1183
Normal Vector for Support 1&2	0.1443	-0.9894	0.2656
Normal Vector for Support 3&4	-0.1443	0.9894	-0.2656

The five axis positioner has its own coordinate system and to carry out manipulations using this positioner the data needs to be converted from the bone coordinate system to the fixture coordinate system. The X and the Z axis get interchanged and there is a difference of 57.404 mm between the two origins along X axis.

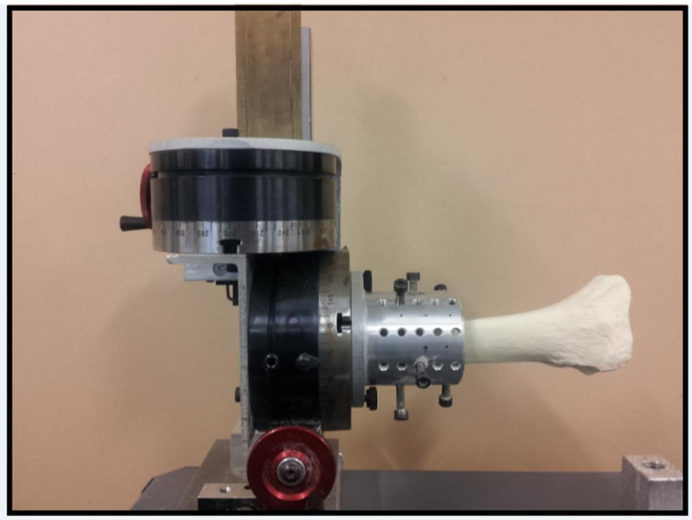

Figure 40 Potted bone mounted on five axis positioner

Taking these into account the harvesting data changes to:

Table 6 Data after mapping to fixture coordinate system

	X Coordinate	Y Coordinate	Z Coordinate
Implant Center	80.2681	-60.5924	-75.3915
P1	82.7641	-69.0536	-74.0697
P2	77.3368	-66.3426	-69.3320
P3	84.3400	-74.990	-73.2038
P4	84.3400	-69.5688	-63.7292
Normal Vector for Support 1&2	0.2656	-0.9894	0.1443
Normal Vector for Support 3&4	-0.2656	0.9894	-0.1443

The next step is to select a normal vector for support. The one which makes the smallest angle with ó+ôve X axis and is also giving a plausible solution considering limitation of axis B is to be selected. The angle made by the normal vector for supports 1&2 with X axis is 1.311 radians and the angle made by the normal vector for supports 3&4 with X axis is 1.830 radians. Even though the normal vector for support 1&2 makes a smaller angle it does not get selected because it results in a rotation which is not possible on the five axis positioner physically, therefore the normal vector for supports 3&4 gets selected. This approach is subsequently used to determine the rotational angles for the rotary axes on the positioner.

The rotary angles determined are given in Table 7 Rotation angles for the positioner

Table 7 Rotation angles for the positioner

Sr. No.	Axis	Rotational Angle	Sense of Rotation
1.	A	8.299	Counter Clockwise
2.	B	104.877	Clockwise

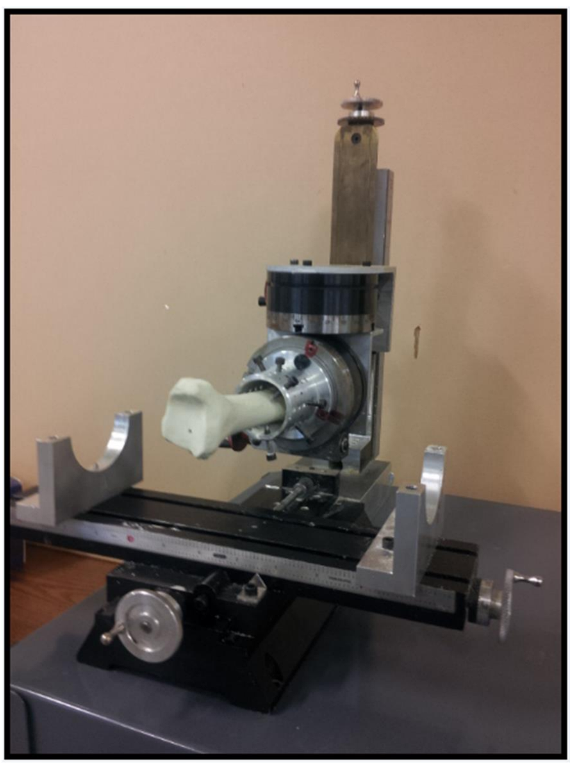

Figure 41 After rotation

After carrying out these two rotations sequentially, the coordinates are

Table 8 Data after rotations on the positioner

	X Coordinate	Y Coordinate	Z Coordinate
Implant Center	-68.0392	-64.9770	-83.3438
P1	-76.9518	-65.1732	-83.2618
P2	-73.6312	-60.4584	-83.2618
P3	-83.1594	-65.1733	-83.2618
P4	-76.5118	-55.7446	-73.1038
Normal Vector for Support 1&2	-1.0346	0.0	0.0
Normal Vector for Support 3&4	1.0346	0.0	0.0

Using a FARO arm, the center of the disc was found to be (208.203, -188.794, -104.553). Taking 20 mm as the distance between disc and the implant center, the translations were determined in Table 9

Table 9 Translational distances on the positioner axes

Sr. No	Axis	Translation (mm)
1	Y	-123.816
2	X	256.242
3	Z	-21.204

After carrying out these translations sequentially, the coordinates are also determined Table 10

Table 10 Data after the translations on the positioner

	X	Y	Z
Implant Center	188.203	-188.794	-104.553
P1	179.291	-188.990	-104.466
P2	182.611	-184.275	-99.3867
P3	173.083	-188.990	-104.466
P4	179.724	-179.561	-94.308
Normal Vector for Support 1&2	-1.0346	0.0	0.0
Normal Vector for Support 3&4	1.0346	0.0	0.0

Once the center of the disc and center of the implant are aligned, the support locations can be determined on the grid. The locations are simply Y and Z Coordinates in the YZ plane and the supports can be inserted in the closest hole on the discs corresponding to the distances.

Table 11 The Y&Z locations of the supports on the disc

Support No.	Horizontal distance on the Grid (mm)	Vertical distance on the Grid (mm)
1	-0.19	0.08
2	9.23	10.24
3	-0.19	0.08
4	4.51	5.16

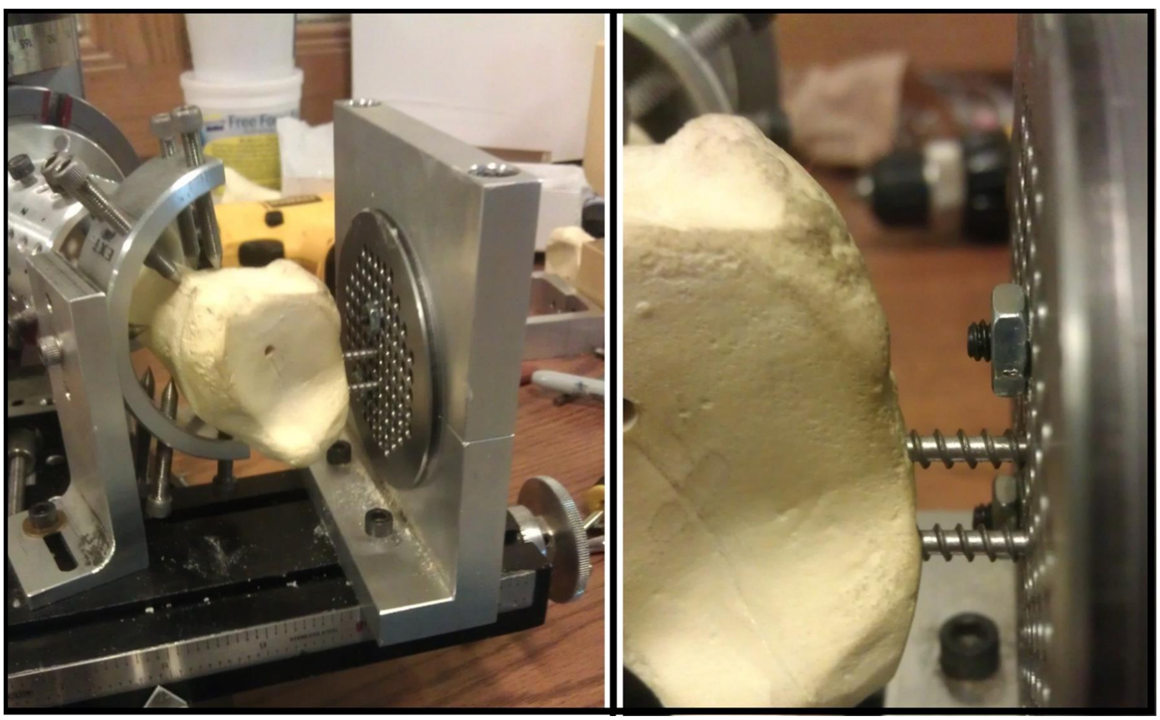

Figure 42 Support insertion into the bone from disc 1

Figure 43 Sawing of the bone after inserting the supports from disc 1

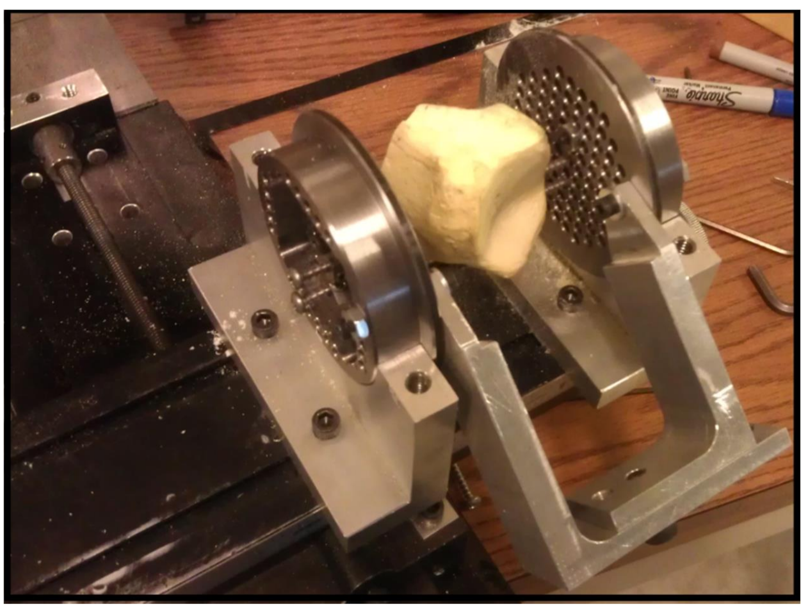

Figure 44 Support insertion from disc 2 and mounting of transfer handle

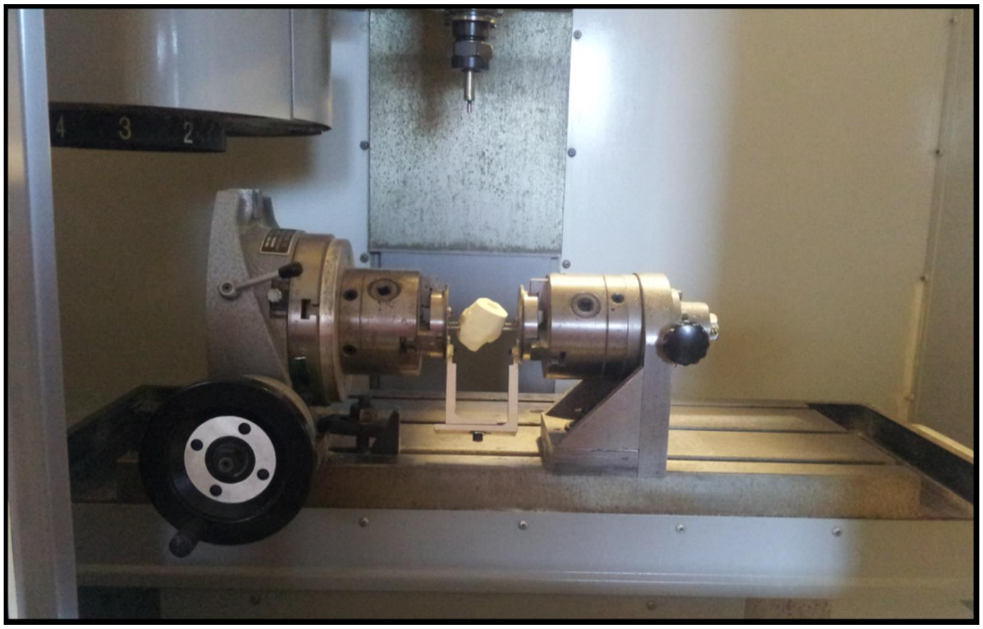

Figure 45 Bone stock loaded into CNC machine

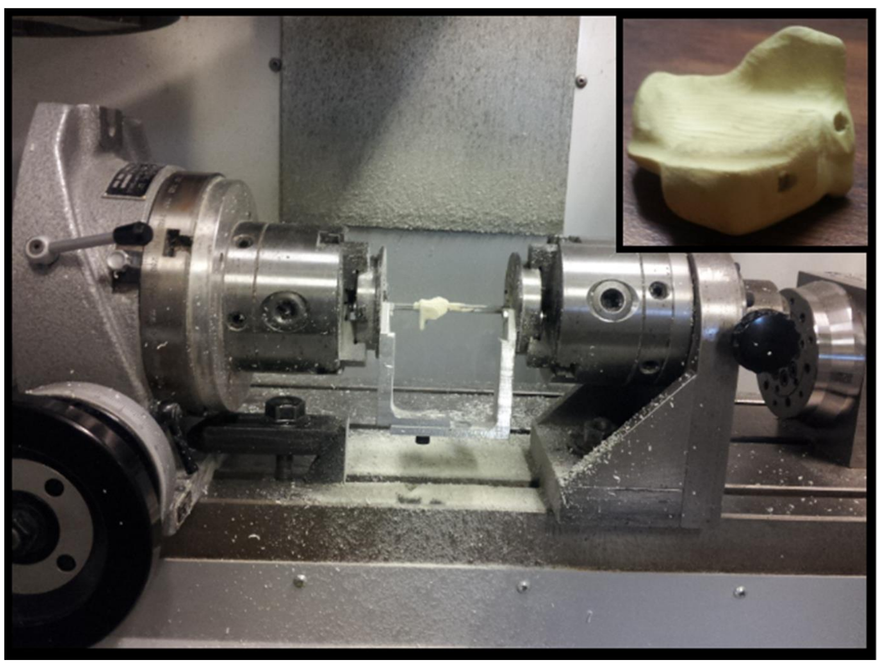

Figure 46 Machined implant

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

This thesis presented a method to build a machining fixture that mimics the required round stock that aids in the application of CNC-RP. A dedicated method was developed to determine the transformations on a five axis positioner to orient and position donor bone stock material for the rapid manufacturing of implants using CNC-RP. The implementation of these algorithms showed that using inverse kinematics, a transformation solution can easily be obtained to orient the stock. This work illustrates the ability to use a five axis positioner to orient and position a stock to externally add sacrificial supports prior to machining. Having said that, if sacrificial supports for some reason (like anomalous stock geometry) could not be built by the conventional way during machining; using a similar approach to external supports can be added for more conventional machining of other component types beyond bone implants.

5.2 Future work

Prior to actual machining, the output transformations from this thesis can be applied and the resulting orientation of the cut stock can be analyzed in solid cutting simulation software to identify the positioning errors. The transformations of the five axis fixture can be automated to obtain accuracy and precision in positioning and this would also eliminate manual error. A generic multi axis postprocessor with visual graphic aid can be developed which can completely output transformations for different five axis fixture configurations effectively.

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